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CONFLICT PREDICTION

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CONFLICT PREDICTION

FINAL REPORT

International Business Machines Corporation
Federal Systems Division
FAA Project
NAS Advanced Programming

June, 1970

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FOREWORD

This paper is concerned with the problem of predicting conflicts in the enroute air traffic environment. The overall design presented herein is based on an interface with the NAS 1b system. However, the basic scheme is not dependent on the Model 1 environment. The x, y and z position and velocity components of the aircraft are the only data required for the performance of the prediction function.

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1.0 Description of the Problem

The goal of the National Airspace System is to provide safe and efficient use of the nation's airspace. In carrying out this goal, one of the services provided by the FAA is separation service among aircraft flights conducted under Instrument Flight Rules (IFR). This service reduces conflict situations by insuring IFR aircraft adequate separation from all other IFR aircraft while operating in controlled airspace.

The responsibility for providing IFR separation service rests with the controller. Using his knowledge of the intent of the pilot, the present position and altitude of the aircraft, and the judgement he has developed through years of experience, the controller is tasked to recognize potential conflict situations and to issue control orders to the aircraft intended to keep them separated.

This paper addresses the problem of conflict recognition. It proposes to incorporate as a separate function in the NAS Model 1 system a conflict prediction algorithm which, using the information available in the system, will monitor IFR aircraft and notify the controller of potential or existing conflict situations.

2.0 Conflict Prediction Overview

The Conflict Prediction algorithms described in this paper will conflict check enroute IFR aircraft for potential violation of IFR separation standards. The prediction process will conflict check IFR aircraft which are operating under radar and/or non-radar flight rules. Aircraft flying according to Visual Flight Rules (VFR) will not be processed.

The prediction process will be accomplished by selecting from the NAS Model 1 data tables pairs of aircraft which are flying within the same altitude level. Each pair being conflict checked will be projected though space using a two dimensional (in the X-Y plane), straight line, constant velocity extrapolation of position. The extrapolation process will be terminated by a look ahead time limit based on data available in the system for the aircraft involved.

Next route segment information will be used in the prediction process if one or both of the aircraft are scheduled to execute a turn before the maximum look ahead time is reached. The position of the two aircraft will be updated to the time that the turn will occur and the prediction process repeated using the new route segment heading information.

Radar tracked IFR aircraft which have no supporting flight plan data (i.e., FREE tracked aircraft) will be conflict checked by having their flight paths extrapolated using present position/velocity tracking information. Non-radar IFR aircraft will be conflict checked using computer calculated position and velocity components.

3.0 Separation Standards

The separation standards required for IFR aircraft are specified in the ATC Procedures Manual, AT P 7110.1B. Since Conflict Prediction will be programmed using those standards as specifications, it is appropriate that the following sections of the ATC Procedures Manual be included as part of this paper.

IFR PROCEDURES:	220	Separation
	221	Vertical Separation
	222	Longitudinal Separation
	223	Lateral Separation
RADAR PROCEDURES:	320-323	Separation

220 SEPARATION

220.1 Separate IFR and special VFR aircraft by the minima and methods described in this section.

220.2 Use DME procedures and minima only when direct pilot-controller communications are maintained.

220.3 Do not apply visual separation (226) or issue VFR or VFR conditions on top (227) clearances in positive control areas.

221 Vertical Separation

221.1 Separate IFR aircraft by assigning different altitudes using the following minima between altitudes:

A. Up to and including FL 290: *1,000 feet.*
B. Above FL 290: *2,000 feet.*

221.2 Assign an altitude to an aircraft after the aircraft previously at that altitude has reported leaving it. However, when severe turbulence is reported, assign an altitude only after the aircraft previously at that altitude has reported at or passing through another altitude separated from the first by the appropriate minimum in 221.1.

Phraseology:

REPORT LEAVING/REACHING [altitude].

REPORT LEAVING ODD/EVEN ALTITUDES/ FLIGHT LEVELS.

→ SAY YOUR ALTITUDE.

221.3 When pilots of aircraft in direct radio communication with each other during climb and descent concur, you may authorize the lower aircraft, if climbing, or the upper aircraft, if descending, to maintain vertical separation (221.1).

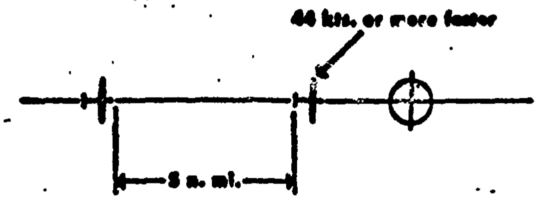
Phraseology:

MAINTAIN AT LEAST ONE/TWO THOUSAND FEET ABOVE/BELOW [aircraft identification].

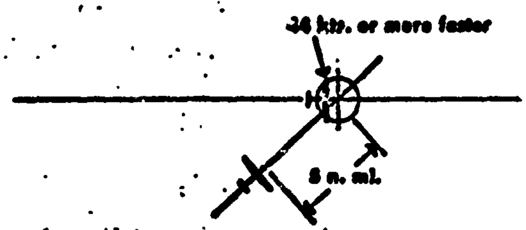
222 Longitudinal Separation

222.1 Separate aircraft on the same, converging, or crossing courses by an interval expressed in minutes of flying time or a specified distance, using the following minima:

A. When the leading aircraft maintains a speed at least 44 knots faster than the following aircraft: *Five miles* between aircraft using DME; or *three minutes* between other



222.1A ILLUSTRATION 1



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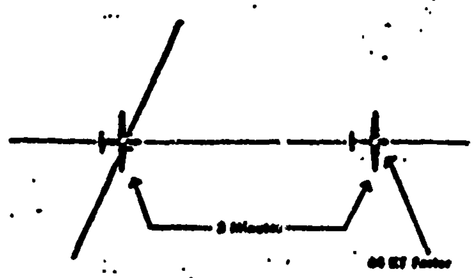

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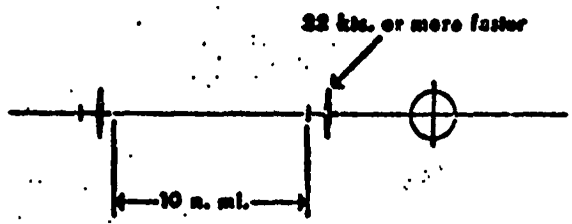
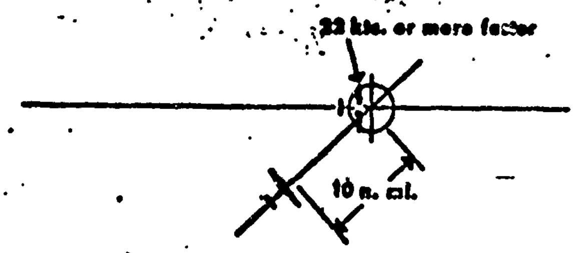


222.1B ILLUSTRATION 1



222.1B ILLUSTRATION 2

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aircraft, if, in either case, one of the following conditions is met: ①

1. A departing aircraft follows a preceding aircraft which has taken off from the same or an adjacent airport.

2. A departing aircraft follows a preceding en route aircraft which has reported over a fix serving the departure airport.

3. When the leading aircraft maintains a speed at least 22 knots faster than the following aircraft: *10 miles* between aircraft using DME; or *five minutes* between other aircraft, if, in either case, one of the following conditions exists: ①

1. A departing aircraft follows a preceding aircraft which has taken off from the same or an adjacent airport.

2. A departing aircraft follows a preceding en route aircraft which has reported over a fix serving the departure airport.

3. An en route aircraft follows a preceding en route aircraft which has reported over the same fix.

C. When an aircraft is climbing or descending through the altitude of another aircraft:

1. Between aircraft using DME: *10 miles*, if the descending aircraft is leading or the climbing aircraft is following. ①

2. Between other aircraft: *Five minutes*, if all of the following conditions are met— ①

a. The descending aircraft is leading or the climbing aircraft is following.

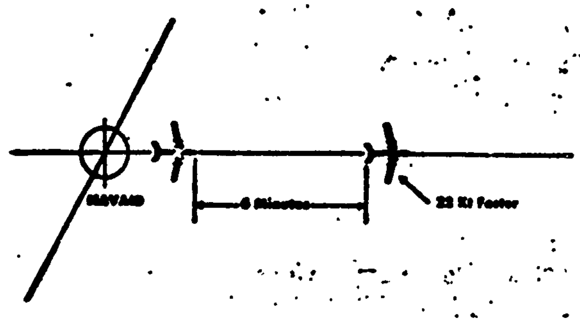
b. The aircraft were separated by not more than 4,000 feet when the altitude change started.

c. The change is started within 10 minutes after a following aircraft reports over a fix reported over by the leading aircraft or has acknowledged a clearance specifying the time to cross the same fix.

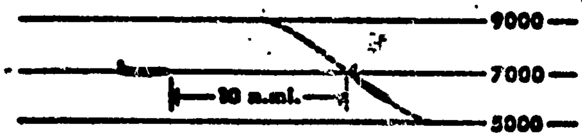
D. When the conditions of 222.1A, B, or C cannot be met: *20 miles* between aircraft using DME; or *10 minutes* between other aircraft. ①

E. Between aircraft, when one aircraft is using DME and the other is not: *30 miles* if both the following conditions are met: ①

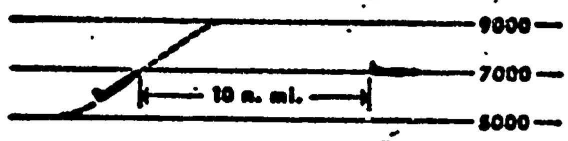
1. The aircraft using DME derives distance information by reference to the same navaid



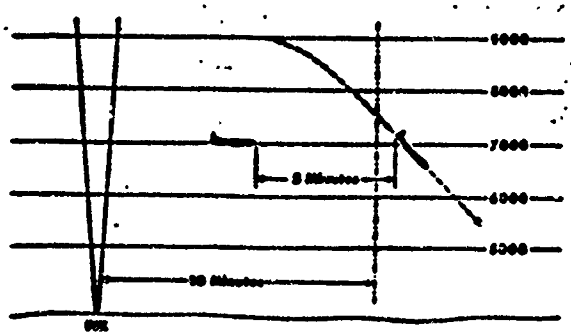
222.1B ILLUSTRATION 3



222.1C1 ILLUSTRATION 1



222.1C1 ILLUSTRATION 2



222.1C2 ILLUSTRATION 1

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over which the aircraft not using DME has reported.

2. The aircraft not using DME is within 15 minutes of the navaid.

222.2 Separate aircraft traveling opposite courses by assigning different altitudes consistent with approved vertical separation (221.1) from *10 minutes before until 10 minutes after they are estimated to pass.* Vertical separation may be discontinued after one of the following conditions is met: ①

A. Both aircraft have reported passing navaids or DME fixes indicating they have passed each other.

B. Both aircraft have reported passing the same intersection and they are at least three minutes apart.

222.3 Separate aircraft longitudinally by requiring them to do one of the following, as appropriate:

A. Depart at a specified time.

B. Arrive at a fix at a specified time.

Phraseology:

CROSS (fix) AT OR BEFORE (time).

CROSS (fix) AT OR LATER THAN (time).

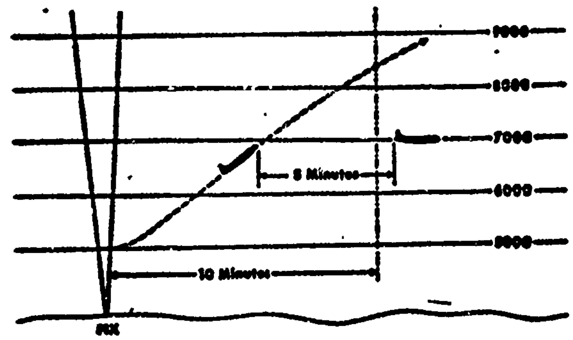
C. Hold at a fix until a specified time.

D. Change altitude at a specified time or fix.

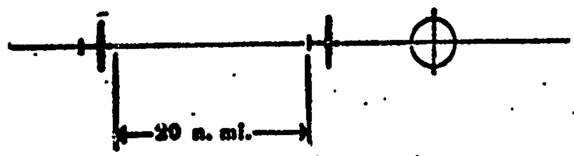
222.4 When pilots of aircraft on the same course in direct radio communication with each other concur, you may authorize the following aircraft to maintain longitudinal separation of *10 minutes; or 20 miles*, if they are using DME.

Phraseology:

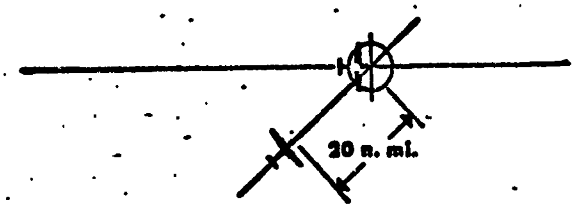
● MAINTAIN AT LEAST ONE ZERO MINUTES'/TWO ZERO MILES' SEPARATION FROM (aircraft identification).



222.1C2 ILLUSTRATION 2



222.1D ILLUSTRATION 1



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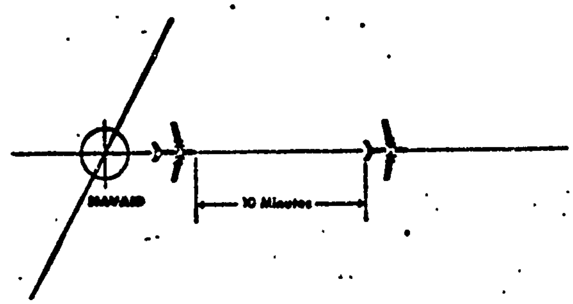

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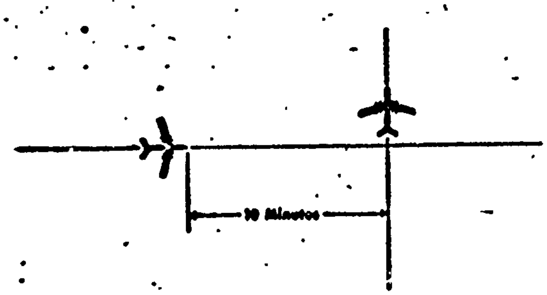

222.1D ILLUSTRATION 4

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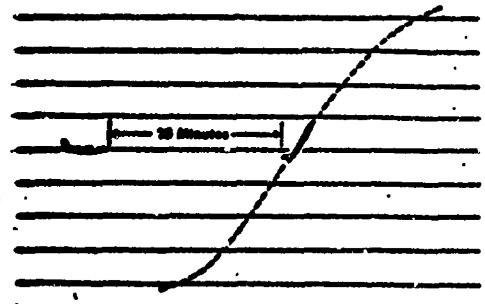

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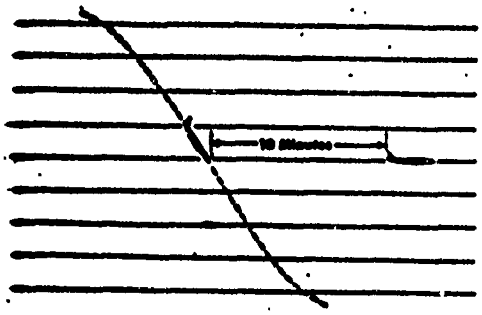

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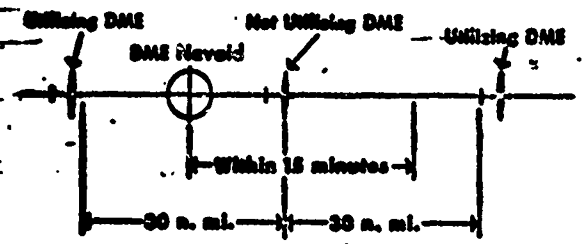
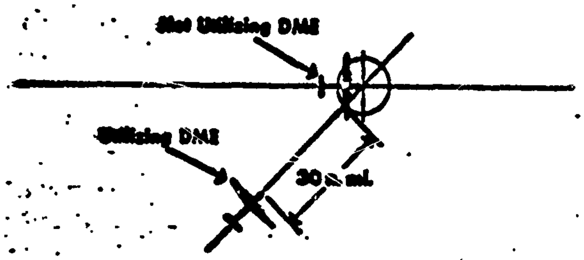
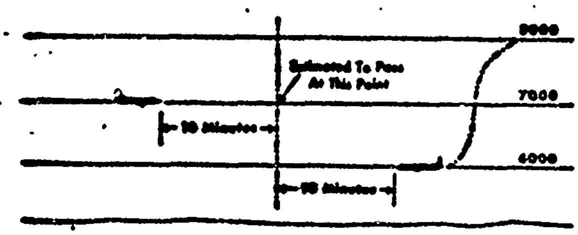


222.1E ILLUSTRATION 1



222.1E ILLUSTRATION 2



222.2 ILLUSTRATION

223 Lateral Separation

223.1 Separate aircraft by one of the following methods:

A. Clear aircraft on different airways or routes whose widths do not overlap. Ⓧ

B. Clear aircraft below 18,000 to proceed to and report over or hold at different geographical locations determined visually or by reference to navaids. Ⓘ

C. Clear aircraft to hold over different fixes whose holding pattern airspace areas do not overlap each other or other airspace to be protected.

D. Clear departing aircraft to fly specified headings which diverge by at least 45 degrees. Ⓘ

223.2 Protect airspace along other than established airways or routes: Ⓧ

A. Direct courses and course changes 15 degrees or less: FL 600 and below—*Four miles on each side of the route to a point 51 miles from the navaid, then increasing in width on a four and one-half degree angle to a width of 10 miles on each side of the route at a distance of 130 miles from the navaid.* Ⓘ

B. Course changes more than 15 degrees:

1. Below 18,000: Same as A. Ⓧ

2. From 18,000 to FL 230 inclusive: *14 miles on the overflown side and 10 miles on the opposite side, beginning at the point where the course changes.*

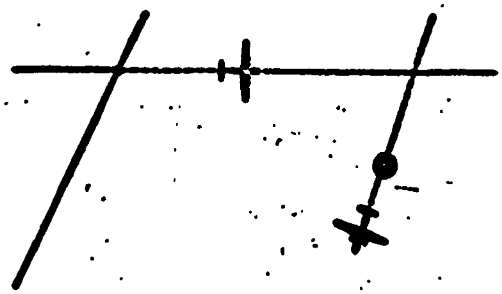
3. Above FL 230 to FL 600 inclusive: *17 miles on the overflown side and 10 miles on the opposite side, beginning at the point where the course changes.*

C. After course changes specified in B 2 and 3 are completed and the aircraft is back on course, the minima in A may be used.

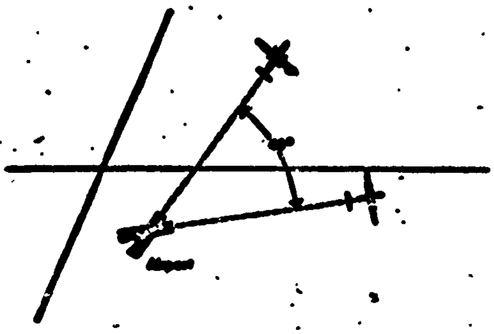
223.3 Unused.

223.4 Consider separation to exist between aircraft established on radials of the same navaid that diverge by at least 15 degrees when either aircraft is beyond the airspace to be protected for the other aircraft. Ⓘ

223.1A NOTE.—Airspace protected for airways is based on airway widths described in FAR 71.5, and airspace protected for routes will be consistent with widths described in FAR 71.5.

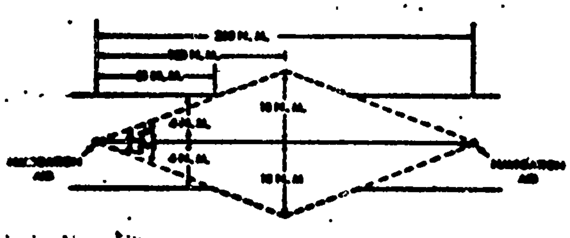


223.1B ILLUSTRATION



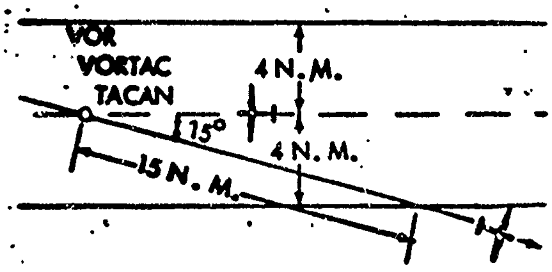
223.1D ILLUSTRATION

223.2 REFERENCE.—Definition of established airways and routes, 121.



223.2A ILLUSTRATION

223.2B1 REFERENCE.—Usable limits of H class navaids below 18,000, 283.2.



223.4 ILLUSTRATION 1

223.5 Apply lateral DME separation by requiring aircraft using DME to fly an arc about a navaid at a specified distance, using the following minima:

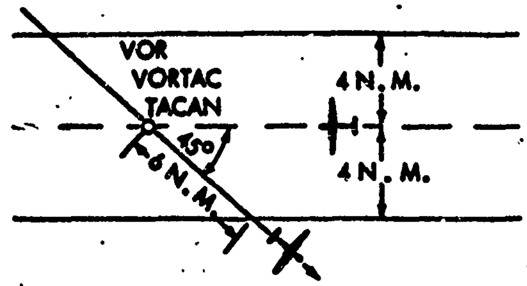
A. Between different arcs about a navaid: *10 miles.* ①

B. Between an arc about a navaid and the boundary of a holding pattern airspace area to be protected: *Five miles.* ①

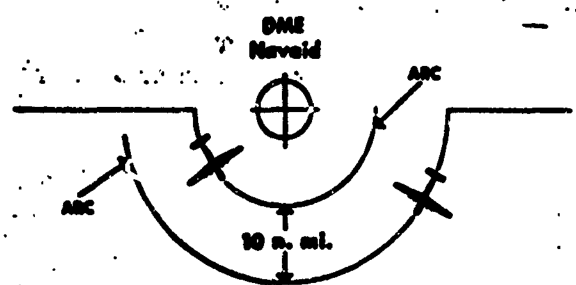
Phraseology:

VIA [number of miles] MILE ARC [direction] OF [name of DME navaid].

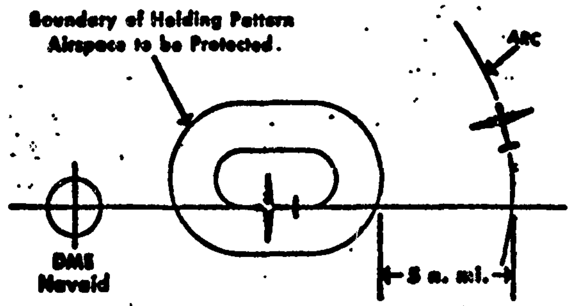
223.6 Protect the airspace 10 miles on each side of the course of an aircraft using Doppler navigational equipment. ⑧



223.4 ILLUSTRATION 2



223.5A ILLUSTRATION



223.5B ILLUSTRATION

223.6 NOTE.—Trans World Airlines is currently the only air carrier authorized to use Doppler navigation within U.S. control areas. These aircraft will ordinarily describe route of flight by degree/distance fixes.

320 SEPARATION

321 Procedures

321.1 Radar separation may be applied between:

A. Radar-identified aircraft.

B. An aircraft taking off and another identified IFR aircraft when the aircraft taking off will be identified within one mile of the end of the runway.

C. A radar-identified aircraft and an IFR aircraft not radar-identified when the former is climbing or descending through the altitude of the latter, and the following conditions exist:

1. The performance of the primary radar system is adequate and primary radar targets are being displayed on the scope being used.

2. A SAGE display is not being used.

3. The airspace in which separation is applied is not less than *six miles* (*10 miles* if 40 miles or more from the antenna site) from the edge of the radar display.

4. Flight data on the unidentified IFR aircraft indicates it is a type which can be expected to give an adequate primary return in the area where separation is applied.

5. The identified aircraft is vectored on a flight path different from the route of the unidentified IFR aircraft before descent or climb.

6. Radar separation is maintained from all observed primary and radar beacon targets until nonradar separation is established from the unidentified IFR aircraft.

321.2 Apply radar separation:

A. Between the centers of primary radar targets. Do not allow a primary target to touch another primary target or a beacon control slash.

B. Between the ends of beacon control slashes.

C. Between the end of a beacon control slash and the center of a primary target.

D. Between the centers of targets when using a SAGE display. Ⓢ

321.3 Use beacon targets for separation purposes only if beacon range accuracy is verified by one of the following methods: Ⓢ

A. Correlate beacon and primary targets of the same aircraft (not necessarily the one being

321.2D NOTE.—Because targets on SAGE displays are uniformly small, there are no circumstances under which two targets can touch when separation in accordance with the minima in 323 is applied between target centers.

provided separation) to assure that they coincide.

B. When beacon and primary targets of the same aircraft do not coincide, correlate to assure that any beacon displacement agrees with the specified distance and direction for that particular radar system.

C. Refer to beacon range monitoring equipment where so installed.

321.4 If beacon range accuracy cannot be verified, use beacon targets for traffic information only.

321.5 Do not use data from SAGE height-finding equipment for separation purposes.

322 Minima—Other than Great Falls ARTCC (RIOTIP)

322.1 Separate aircraft by the following minima:

A. If less than 40 miles from the antenna site: *Three miles.*

B. If 40 miles or more from the antenna site: *Five miles.*

322.2 Vertical separation between aircraft may be discontinued when the following conditions are met:

A. You observe that they have passed each other and their primary targets or beacon control slashes do not touch.

B. Their courses diverge by at least 15 degrees.

322.3 Except as provided in 322.4, separate a departing aircraft from an arriving aircraft on final approach by a minimum of *two miles* if separation will increase to a minimum of *three miles* (*five miles* when 40 miles or more from the antenna) within one minute after take-off.

322.4 Separate a departing aircraft from an arriving aircraft on final approach to another parallel or nonintersecting, diverging runway by applying the following:

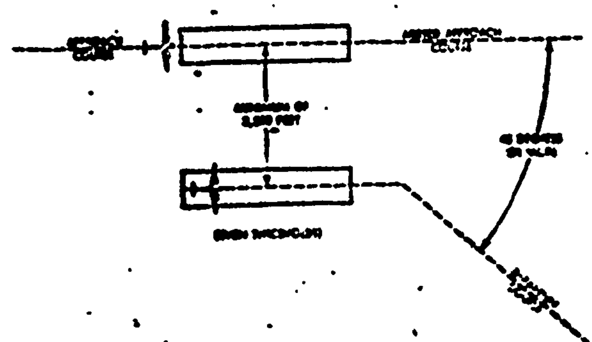
A. Parallel runways—authorize simultaneous operations provided the following conditions exist:

1. The runway configuration is as follows:

a. If the thresholds are even, the runway centerlines are separated by *at least 3,500 feet.* ①

321.3 Note 1.—The check for verification of beacon range accuracy accomplished by correlation of beacon and primary radar targets of the same aircraft is not a check of display accuracy. Therefore, it is not necessary that it be done using the same display with which separation is being provided, nor the same targets being separated.

321.3 Note 2.—SAGE beacon range accuracy is verified by the system and no further verification by the controller is necessary.



322.4A1a ILLUSTRATION

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b. If the thresholds are staggered and:

(1) The approach is made to the runway nearest the arriving aircraft, the runway centerlines are laterally separated by *at least 1,000 feet and the thresholds horizontally staggered by at least 500 feet for each 100 feet of centerline separation below 3,500 feet.* ①

(2) The approach is made to the runway farthest from the arriving aircraft, the runway centerline separation exceeds 2,500 feet by *at least 100 feet for each 500 feet the thresholds are staggered.* ①

2. The departure course will diverge immediately after take-off from the missed approach course by *at least 45 degrees until minimum radar separation distance is achieved and can be maintained.*

3. Departing aircraft that have not commenced take-off are held or appropriate clearances issued to those committed to take-off when an arriving aircraft is observed to deviate from the approach/missed approach course sufficiently to cause a potential conflict.

B. Nonintersecting, diverging runways—authorize simultaneous operations provided the following conditions exist:

1. The departure course upon or immediately after take-off diverges from the missed approach course by *at least 45 degrees until minimum radar separation distance is achieved and can be maintained.*

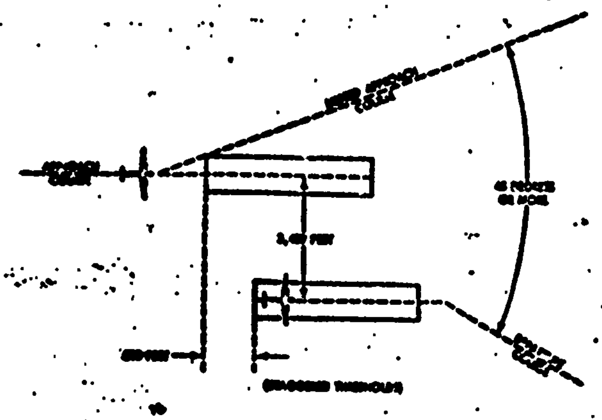
2. The distance between the centerline or extended centerline of the landing runway and the centerline of the take-off runway (measured from the point where the take-off is commenced) is as follows:

a. If the runways diverge by 30 degrees or more—*at least 1,000 feet.* ①

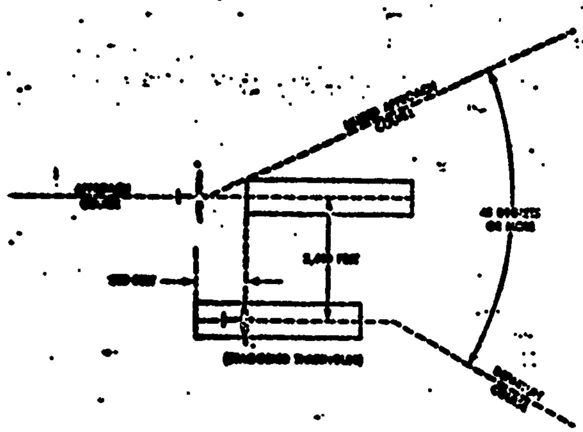
b. If the runways diverge by 15 to 29 degrees inclusive—*at least 2,000 feet.* ①

c. If the runways diverge by 14 degrees or less—*at least 3,500 feet.* ①

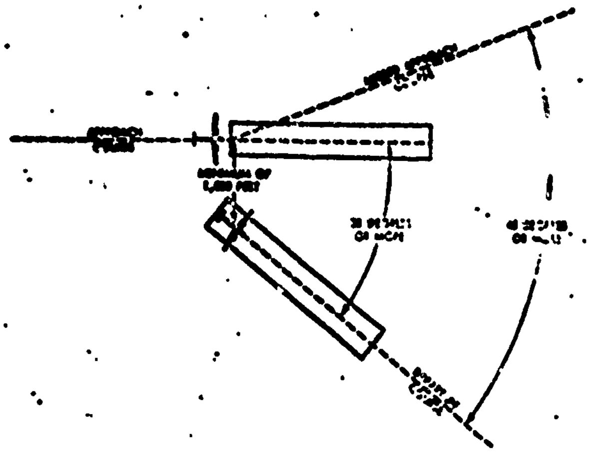
3. Departing aircraft that have not commenced take-off are held or appropriate clearances issued to those committed to take-off when an arriving aircraft is observed to deviate from the approach/missed approach course sufficiently to cause a potential conflict.



322.4A1b(1) ILLUSTRATION



322.4A1b(2) ILLUSTRATION



322.4B2a ILLUSTRATION

322.5 If coordination between the controllers concerned has not been effected, separate radar-controlled aircraft from the boundary of adjacent airspace in which radar separation is also being used by the following minima:

A. When less than 40 miles from the antenna: *One and one-half miles.*

B. When 40 miles or more from the antenna: *Two and one-half miles.*

322.6 Separate radar-controlled aircraft from the boundary of airspace in which nonradar separation is being used by a minimum of *three miles* (*five miles* when 40 miles or more from the antenna). However, this separation is not required if the radar-controlled aircraft are either climbing or descending and they are definitely outside of the airspace in which nonradar separation is being used.

322.7 Separate a radar-controlled aircraft climbing or descending through the altitude of an aircraft that has been tracked to the edge of the scope by a minimum of *three miles* (*five miles* when 40 miles or more from the antenna) from the edge of the scope until nonradar separation has been established.

322.8 When using a radar display with a previously specified beacon target displacement to separate a beacon target from a primary target, nonradar controlled airspace, obstructions, or terrain, apply the following correction factors to the applicable minima:

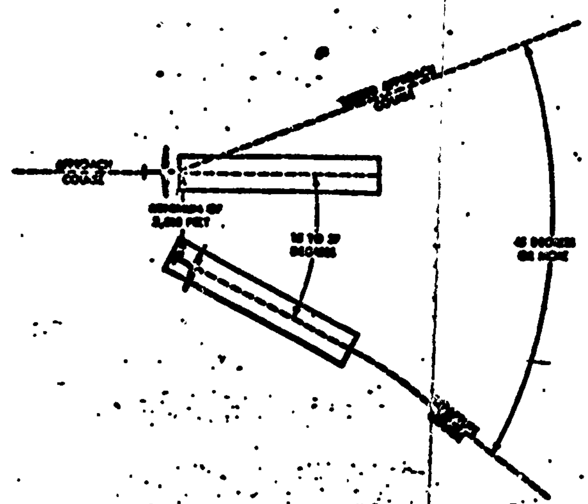
A. For any displacement of one mile or less: *Add one mile.*

B. For any displacement of more than one mile but not more than two miles: *Add two miles.*

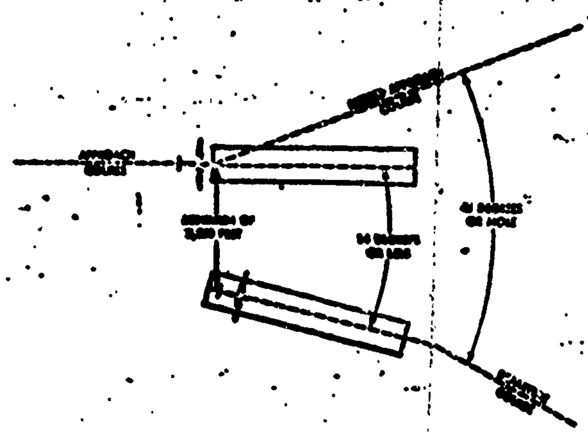
322.9 When using a radar display whose primary radar video is processed by the GPA 102/103 modification to a joint-use radar system, apply the following correction factors to the applicable minima:

A. If less than 40 miles from the antenna site: *Add one mile.*

B. If 40 miles or more, but not over 200 miles, from the antenna site: *Add three miles.*



322.4B2b ILLUSTRATION



322.4B2c ILLUSTRATION

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322.10 Within 40 miles of an antenna site, separate aircraft from prominent obstructions shown on the radar scope (displayed on the video map, scribed on the map overlay, or displayed as a permanent echo) by a minimum of *three miles.* ⊗

322.10 NOTE.—The determination of what constitutes a prominent obstruction is made locally after coordination with appropriate Flight Standards Service representatives.

322.11 Vertical separation of aircraft above a prominent obstruction, which is displayed as a permanent echo, may be discontinued after you observe that the aircraft has passed it.

323 Minima—Great Falls ARTCC (NOTIP)

323.1 When using SAGE situation displays, separate aircraft by the following minima:

A. Between aircraft anywhere in the area of display: *10 miles.*

B. Between a radar-controlled aircraft climbing or descending through the altitude of a preceding aircraft tracked to the limits of the display and the perimeter of the display: *10 miles* until nonradar separation is achieved.

C. If coordination between the controllers concerned has not been effected, between a radar-controlled aircraft and the boundary of adjoining airspace within which aircraft are being given radar separation: *Five miles.*

D. Between radar-controlled aircraft maintaining a constant altitude and the boundary of adjoining airspace within which aircraft are being provided nonradar separation: *Eight miles.*

E. Between radar-controlled aircraft which are climbing or descending and the boundary of adjoining airspace within which aircraft are being provided nonradar separation: *Three miles.*

324–329 Unused.

4.0 Data Base Requirements

Existing Model 1 Compool tables will provide most of the data required by the Conflict Prediction program. The program may be divided into three main sections: pre-processing, processing and output. The data requirements for each section are outlined in the following paragraphs.

4.1 Pre-processing Requirements

Pre-processing is concerned with the creation and maintenance of the Segregated Altitude Table (SAT). The SAT is updated to reflect changes in the flight status of all active IFR aircraft (i.e., new flights, drop flights, flights executing an altitude maneuver). To accomplish this task, data items contained in the Flight Plan Index Table (FPIN) will be used. A description of the items is given in Table 4.1.

Table 4.1 Pre-processing Data Requirements

	Description of Data	Data Name
FPIN_	Empty/full Indicator	FPEFI
	Flight Status Indicator	FPSTA
	Flight Rule Indicator	FPFRI
	Blocked Altitude Indicator	FPBLK
	Assigned Altitude	FPAAL
	Upper Altitude Limit	FPUAL

Additional data necessary for conflict prediction will be provided by an FPIN-extended table not now in the system. For each entry in the FPIN table, a parallel entry will be made in the FPIN-extended table. The items to be contained in each entry are:

- o FPIN change indicator - one bit used to indicate that the FPIN entry has been modified.
- o SAT status indicator - one bit used to indicate that information on the aircraft has been recorded in the SAT table.
- o flight termination indicator - one bit used to indicate that the FPIN entry for the aircraft has been deleted.
- o SAT level index pointers - two six-bit items, containing the lower and upper levels of SAT in which data for the aircraft has been recorded.
- o altitude status indicator - two bits used to indicate that one of the following conditions exists:
  1. the aircraft is in level flight.
  2. an altitude maneuver is in progress.
  3. the altitude maneuver has been completed.
- o previously assigned altitude(s) - two ten-bit items, containing the previously assigned altitude and the upper altitude limit (if block) for the aircraft.

4.2 Processing Requirements

The processing section contains the conflict prediction algorithms. Aircraft pairs recorded in the same SAT level are conflict-checked to determine if a violation will occur within a prescribed look-ahead time. The Flight Plan Index Table (FPIN), Aircraft Route Record Table (AKRR), and Tracking Data Table (TKDT) contain the data required for this task. The information needed for the prediction process varies according to the mode of the aircraft. A description of the data and of the appropriate items to be accessed for each aircraft mode is given in Table 4.2.

4.3 Output Requirements

When a potential/actual violation has been detected, the responsible sector controllers will be notified. The Plan View Display (PVD) and the Computer Readout Device (CRD) will be used to communicate the presence of the conflict situation.

A conflict message will be displayed on the D controller's CRD when a violation of <u>radar or non-radar</u> separation standards is detected. The necessary data (see Section 8.2) will be obtained from Compool tables FPIN, AKRR and TKDT, stored in a LEASEd block and SENDed to CRDO. To accomplish this an additional intercommunication (QU) message format is required. Some modifications must also be made to

Table 4.2 Processing Data Requirements

Data Base Requirements	Aircraft Mode					
	FLAT	FLAT TURN	FLAT COAST	FREE	FREE COAST	NON-RADAR
Present Position	TKCOR	TKCOR	TKCOR	TKCOR	TKCOR	FPCOR
Ground Speed	AKGSP	____	AKGSP	*	*	AKGSP
Velocity Components	FPSPO	TKVCO	FPSPO	TKVCO	TKVCO	FPSPO
Heading	AKBER	____	AKBER	*	*	AKBER
Altitude	TKALT/ FPAAL	TKALT/ FPAAL	TKALT/ FPAAL	TKALT	TKALT	FPAAL
Range	RDRNG	____	RDRNG	RDRNG	____	____
Fix Coordinates	AKXCO/ AKYCO	____	AKXCO/ AKYCO	____	____	AKXCO/ AKYCO
CTA	AKTIM	____	AKTIM	____	____	AKTIM
Distance Between Fixes	AKDIS	____	AKDIS	____	____	AKDIS
Previous Fix Pointer	FPPCX	____	FPPCX	____	____	FPPCX
Next Fix Pointer	AKNXE	____	AKNXE	____	____	AKNXE
Last Fix Flag	AKLFI	____	AKLFI	____	____	AKLFI

* Not now available in the system, but will be required.

subprogram CRDO, as routing and composition tasks are needed to prepare conflict (QU) messages for output to the CRD.

The PVD will be used to communicate to the R controller that a violation of radar separation standards has been detected. Route displays will be output only for those aircraft pairs under the jurisdiction of the same controller (i.e., appearing on the same PVD). Control information will be supplied by the Plan View Display Table (PVDT) and the Sector Index Table (SCID). The data required to build the displays will be obtained from FPIN, AKRR and TKDT. The capability of automatically displaying a number of routes simultaneously at any one console does not exist in the present system. To provide for this function, some modifications must be made to subprogram CPVD.

5.0 Conflict Prediction Pre-Processing

Conflict Prediction pre-processing will organize the IFR flight data so as to reduce the processing load placed on the computer system. In terms of processing requirements, Conflict Prediction must by necessity conflict check each IFR aircraft in the system against the other aircraft in the system if it is to insure that separation standards are not violated by any aircraft pair. As pointed out in Appendix A, this requirement results in a processing load that grows rapidly as the number of active IFR aircraft increases.

In the enroute environment, however, this need not be the case. Characteristically, IFR aircraft spend the majority of their enroute flight time in level flight. The enroute altitudes assigned by the ARTCCs are almost always in multiples of one (or two) thousand feet - the basic altitude increment required for vertical separation. Therefore, if the IFR flights in the system are grouped by altitude into levels which meet vertical separation requirements, only the aircraft in the same altitude level need be compared with each other. Aircraft at different altitudes will be safely separated by virtue of being recorded in a separate altitude level group.

Using the data that already exists in NAS, Conflict Prediction pre-processing will create and maintain a Segregated Altitude Table (SAT) to provide the segregation of all active IFR flights by altitude level. The SAT will be divided into subtables for each altitude level. Each subtable will contain, for the aircraft in that level, pointers to the aircraft's flight plan and/or track information.

Maintenance of the SAT will be performed each time the Conflict Prediction subprogram is executed. Before the conflict checking algorithms can be applied to the IFR flights recorded in the system, the Conflict Prediction pre-processing task will scan the Model I data tables checking for

1. new flights (which have recently become active and need to be added to the SAT),
2. terminated flights (which have become void and need to be deleted from the SAT), and
3. existing flights which have had an altitude change and need to be deleted from their prior SAT level and added to their present SAT level.

Ideally, every aircraft in the system will be recorded only once in the SAT. In practice, however, this will not be the case. Some aircraft will be recorded in multiple

SAT levels. This will occur when the aircraft must be conflict checked against multiple SAT altitude levels, such as in the following instances:

1. Mode C equipped aircraft in the process of executing an altitude maneuver,
2. aircraft assigned block altitude, or
3. aircraft assigned altitudes which are not multiples of one (or two) thousand feet.

Additional details concerning the SAT can be found in Appendix A (SAT Filtering Effectiveness) and Appendix B (SAT Design and Maintenance).

6.0 Process Filters

The conflict prediction algorithm will contain a series of computations and tests designed to filter out as quickly as possible those aircraft pairs which are not in conflict. Three filters will be programmed:

1. The altitude filter,
2. the gross range filter, and
3. the convergence/divergence filter.

Since these are the basic filters of the Conflict Prediction process, they will be discussed here. Section 7.0 will discuss the ways in which they will be applied to the prediction process.

6.1 Altitude Filter

The Segregated Altitude Table (SAT) described in Section 5.0 will provide Conflict Prediction with a gross altitude filter. Since the selection of aircraft for conflict checking is based on a SAT grouping by altitude level, only those aircraft pairs recorded in the same SAT level will be tested for possible violations. Hence, the SAT will filter out most aircraft pair combinations which meet vertical separation requirements and therefore cannot be in conflict. A detailed analysis of SAT aircraft filtering effectiveness may be found in Appendix A.

After an aircraft pair has been selected from a particular SAT level, a more precise altitude filtering mechanism will be applied. A test will be made to determine if either aircraft is in the process of an altitude change. If an altitude change is in progress and Mode C data does not exist for the aircraft, then the pair will be dropped from further consideration. Thus, the checking to be performed by Conflict Prediction is reduced to those active aircraft in level flight within the same altitude stratum, and Mode C equipped aircraft in the process of an altitude maneuver.

6.2 Gross Range Filter

Aircraft pairs which remain after altitude filtering will be filtered with respect to their gross range. If the current distance of separation is such that the two aircraft could never violate separation standards in the remaining look ahead time period, even if they were to fly directly at each other, then the pair will be dropped from further processing.

Hence, in figure 6.1, if you assume that aircraft A is located at position (X_A, Y_A) and that aircraft B is located at position (X_B, Y_B), then their present separation r_o is given by the equation

$$r_0 = \sqrt{(X_A - X_B)^2 + (Y_A - Y_B)^2}$$

If the velocity of aircraft A is V_A, and the velocity of aircraft B is V_B, then the maximum distance travelled by both aircraft in the remaining look ahead time interval Δt is equal to

$$(V_A + V_B)\,\Delta t$$

The gross range test will eliminate the aircraft pair from further processing if

$$r_o > (V_A + V_B)\,\Delta t + \Delta r$$

where Δr* is the longitudinal separation parameter for the aircraft.

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* For radar tracked aircraft, $\Delta r = 3$ (or 5) nautical miles. For nonradar aircraft, $\Delta r = 10$ minutes of separation at a velocity of $(V_A + V_B)$.

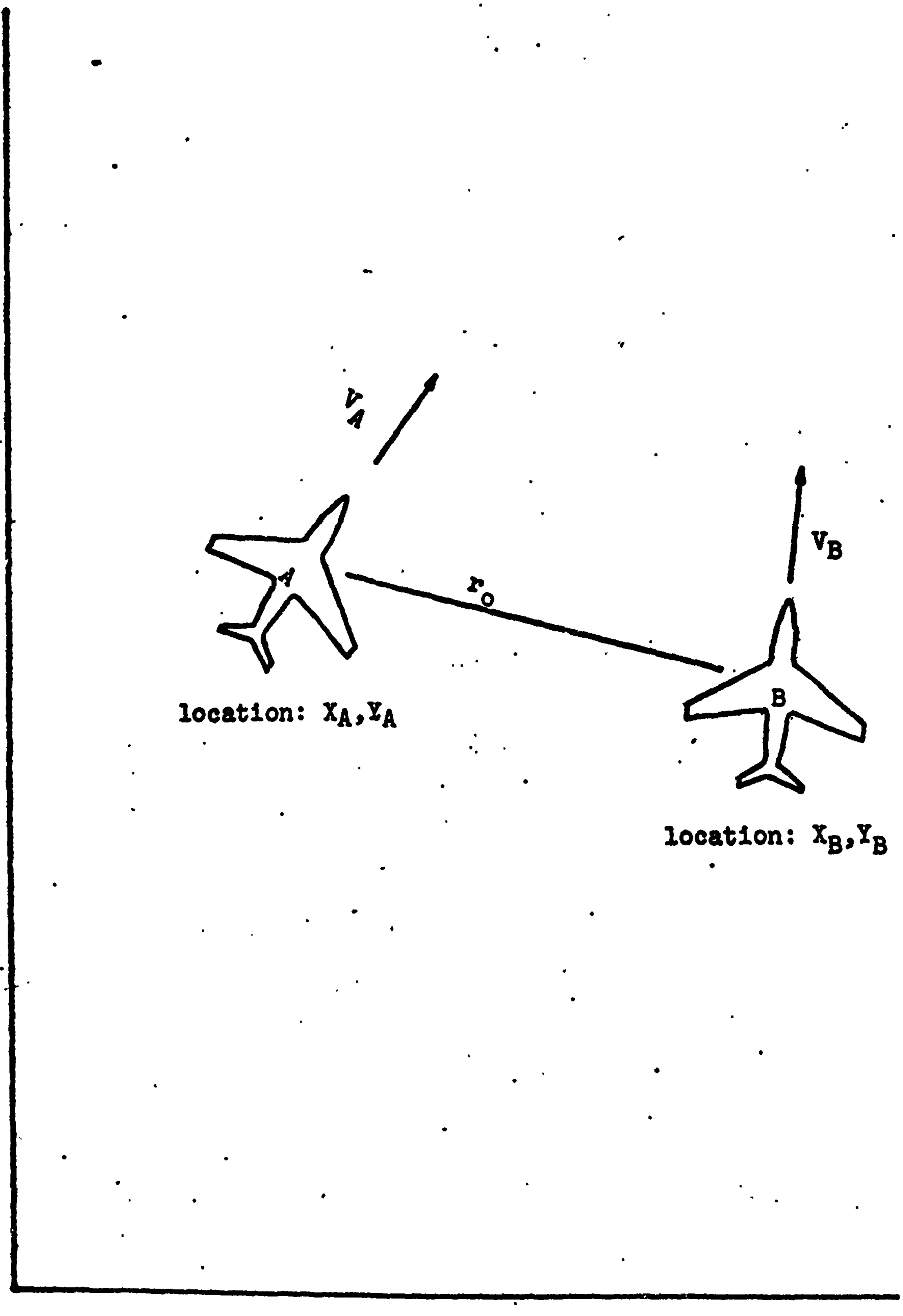

Figure 6.1 Gross Range Filter

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6.3 Convergence/Divergence Filter

If the aircraft pair is not eliminated by the gross range filter, then a determination will be made as to whether the two aircraft are currently diverging on their present route segments. If they are diverging, the pair will be dropped from further consideration on this route segment. The divergence test will not eliminate the pair from further checking but will provide a filter at the route segment level.

The test for divergence is done as follows. In Figure 6.2, assume that aircraft A is located at position (X_A, Y_A) in system coordinates. Its position vector $\vec{r}_A$ is then written as

$$\vec{r}_A = X_A\hat{i} + Y_A\hat{j}$$

where $\hat{i}$ and $\hat{j}$ are the unit vectors in the x and y direction. Its velocity vector $\vec{V}_A$ is defined as the sum of its velocity components $\dot{X}_A$ and $\dot{Y}_A$, or as

$$\vec{V}_A = \dot{X}_A\hat{i} + \dot{Y}_A\hat{j}$$

The position vector for aircraft B ($\vec{r}_B$) and the velocity vector for aircraft B ($\vec{V}_B$) are similarily defined. Based on these definitions, the relative position vector $\vec{r}$ of aircraft B with respect to aircraft A is written as

$$\vec{r} = \vec{r}_B - \vec{r}_A = (X_B - X_A)\ \hat{i}+(Y_B - Y_A)\ \hat{j}$$

The relative velocity vector $\vec{V}$ of aircraft B with respect to aircraft A is written as

$$\vec{V} = \vec{V}_B - \vec{V}_A = (\dot{X}_B - \dot{X}_A)\hat{i} + (\dot{Y}_B - \dot{Y}_A)\hat{j}$$

The test for divergence is done by calculating the value $\vec{r}\cdot\vec{V}$ where

$$\vec{r}\cdot\vec{V} = (X_B - X_A)(\dot{X}_B - \dot{X}_A) + (Y_B - Y_A)(\dot{Y}_B - \dot{Y}_A)$$

If: $\vec{r}\cdot\vec{V} \geq 0$, then the aircraft are either diverging or are maintaining constant separation;

$r\cdot V < 0$, then the aircraft are converging.

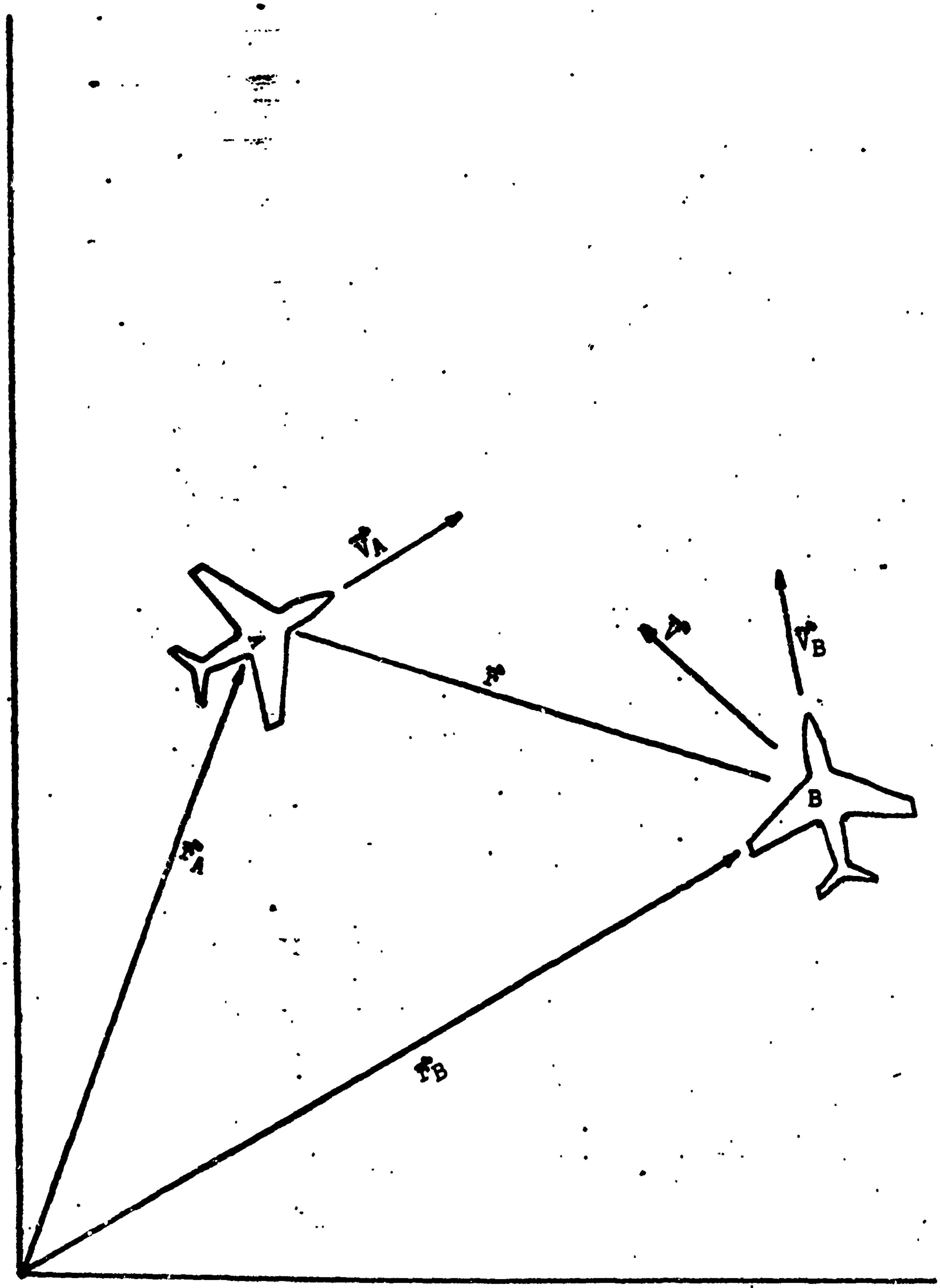

Figure 6.2 Convergence/Divergence Filter

7.0 Conflict Prediction Processing

The basic filters used by Conflict Prediction have been described in Section 6.0 of this paper. This section will describe how these filters, in conjunction with other programmed algorithms, will be applied to determine if a specific aircraft pair are (or will be) in violation of the IFR separation standards.

Two different IFR separation checking algorithms will be included in Conflict Prediction: one algorithm will be used in testing for violations of radar separation standards; the other algorithm will be used in testing for violations of non-radar separation standards. The algorithm used will be selected in the following way:

- o If both aircraft are radar tracked, the algorithm testing for violations of IFR radar separation standards will be used.
- o If either aircraft is not radar tracked, the algorithm testing for violations of IFR non-radar separation standards will be used.

7.1 Radar Tracked Aircraft

In the NAS Model 1b system, SPO-MD-118 defines five modes of tracking.

1. Flight-Plan-Aided-Straight-Line Tracks (FLAT), for enroute reliable tracks which are within lateral association limits of their flight plans.

2. Flight-Plan-Aided-Turn Tracks (FLAT TURN), for FLAT tracks which are in the process of executing a pre-planned turn maneuver.

3. Flight-Plan-Aided Coast (FLAT COAST), for FLAT or FLAT TURN tracks whose track merit indicates the radar data is unreliable.

4. Free Track (FREE), for reliable tracks which are either out of lateral association limits of their flight plans, or else have no flight plan.

5. Free Coast (FREE COAST), for FREE tracks whose track merit indicates the radar data is unreliable.

All of the above tracking modes will be addressed. However, the discussion on processing FLAT TURN mode tracks will be deferred until Section 7.3 (Special Cases).

7.1.1 Radar Separation Standards

The standards for separation of radar tracked IFR flights are specified in the excerpts from the ATC Procedures Manual (AT P71101B) included in Section 3 of this paper. The radar separation criteria which will be programmed are as follows:

- Vertical separation - At altitudes up to and including 29,000 feet a vertical separation of 1,000 feet will be required; above 29,000 feet, the vertical separation requirement increases to 2,000 feet.

o Horizontal separation - If less than 40 miles from the radar antenna site, a horizontal separation of 3 (1-10,1) miles will be required. Forty miles or more from the antenna site, the horizontal separation required is 5 (1-15,1) miles.

The resulting effect of the above interpretation of radar IFR separation requirements is as follows: When Conflict Prediction checks a specific aircraft pair for a potential separation violation, the airspace about one aircraft (referred to as the "parent") will be protected from penetration by the other aircraft (referred to as the "intruder"). The protected airspace is essentially pillbox in shape - a circular area 3 (or 5) nautical miles in radius which extends 1,000 feet (or 2,000 feet) above and below the parent aircraft. A pictorial representation of the parent's protected airspace is shown in figure 7.1.

7.1.2 Programming Technique

To describe the Conflict Prediction process, consider the processing in terms of a pair of radar tracked aircraft which are adhering to their respective flight plans. Since any pair of aircraft processed will have been chosen from the same altitude level of the Segregated Altitude Table (SAT), this implies that either:

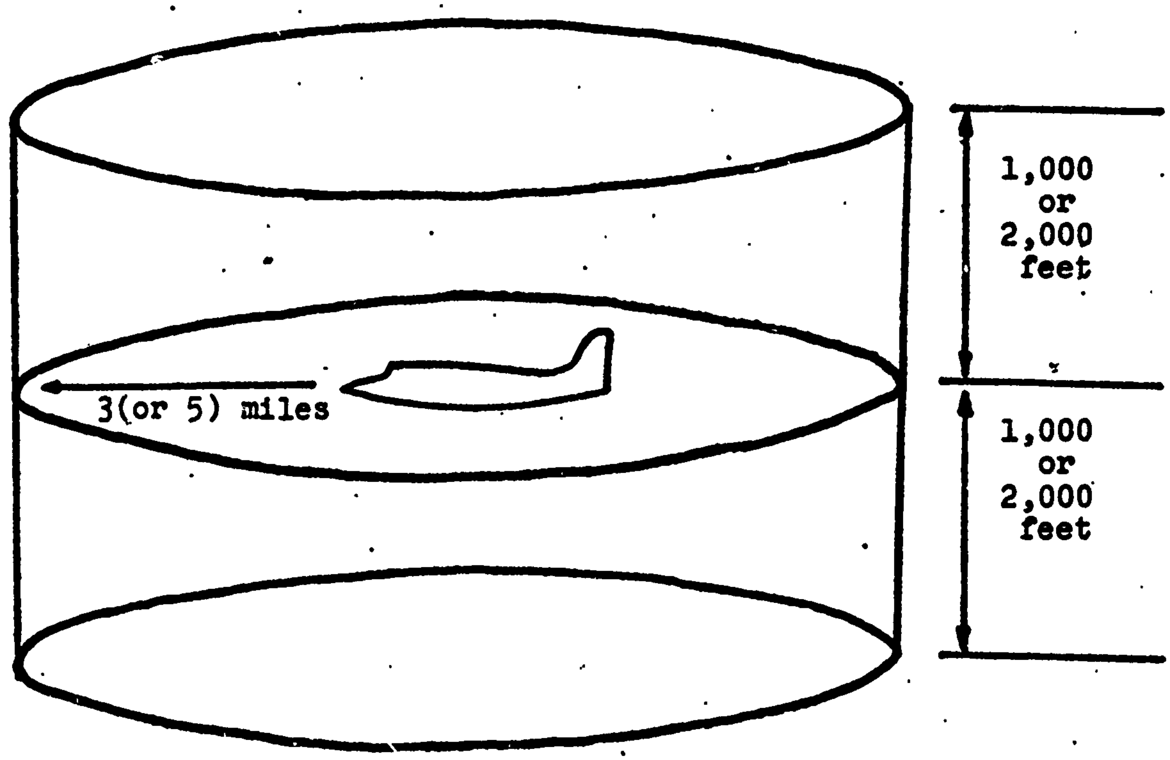

Figure 7.1 Radar Protected Airspace

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1. the aircraft do, at this time, violate vertical IFR separation standards, or

2. may potentially be in violation of IFR separation standards.

Hence, the use of the SAT reduces the conflict prediction problem to a two dimensional question: do the aircraft pair also violate horizontal IFR separation standards?

The general approach used to answer this question can be described by use of figure 7.2. Starting with the track positions of aircraft A and aircraft B at the present time (t_0), the aircraft flight paths will be projected to their next respective fixes using a two dimensional, straight line, constant velocity extrapolation of position. The flight paths of aircraft A and B will then be examined in the time period t_0-t_1 (where t_1 is the CTA of the nearest* fix) to determine if a conflict situation will occur. If a conflict does not occur, the aircraft positions will then be extrapolated to time t_1, the new heading data for the second route leg of aircraft A will be acquired, and the flight path examination repeated for time period t_1-t_2 (where time t_2 again represents the CTA of the fix nearest to the present extrapolated positions of the aircraft). This process will be reiterated until either:

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* "Nearest" in this usage refers to nearest in terms of flight time, not distance.

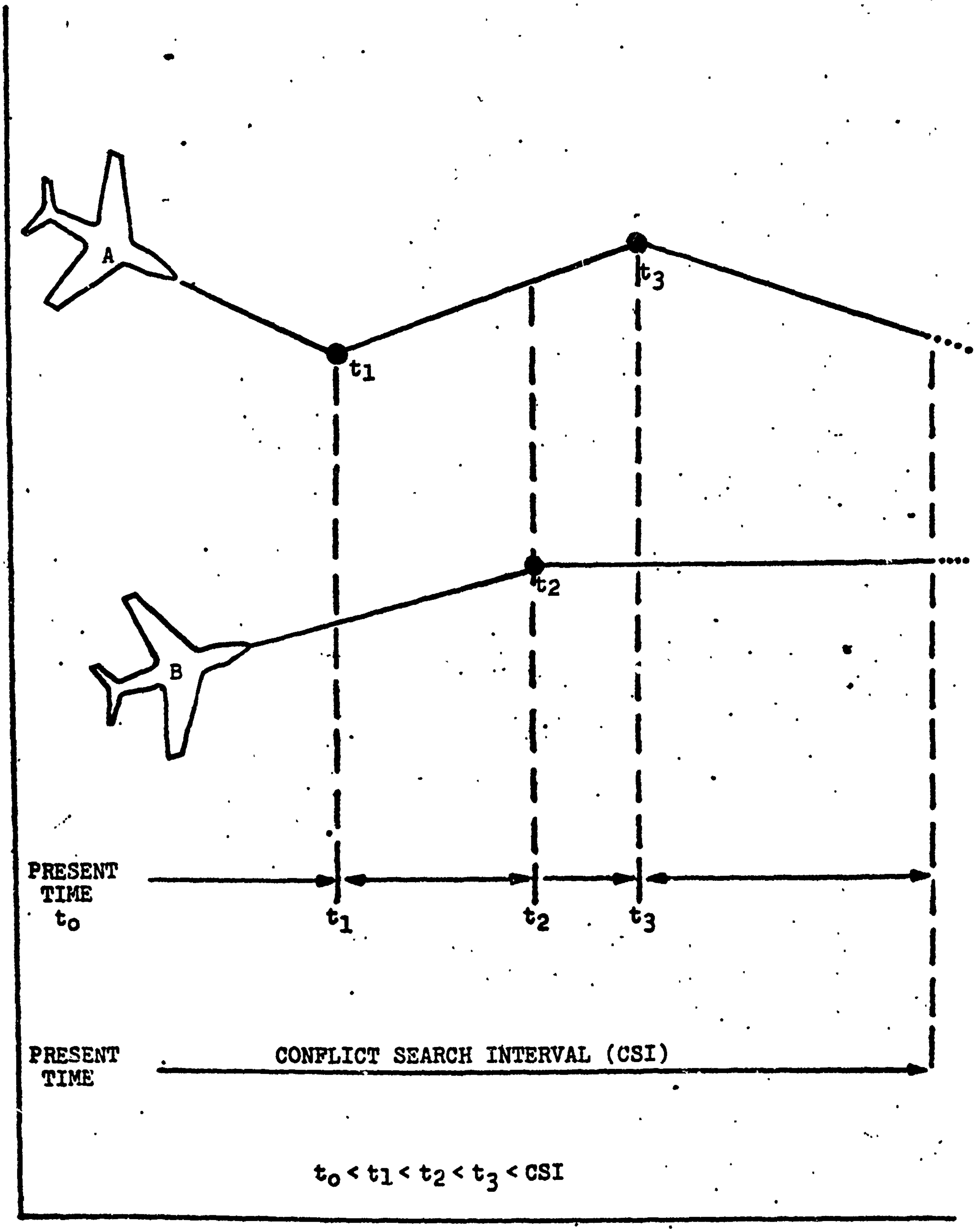

Figure 7.2 Route Leg Projection

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1. aircraft A or aircraft B arrives at its last fix within the center,

2. the total time of route projections exceeds the time limit specified for the Conflict Search Interval (CSI), or

3. a conflict is detected.

The implementation of this approach to conflict prediction processing, along with the application of the process filters described in Section 6.0, is diagrammed in the functional flow chart shown in Figure 7.3. ~~Six~~ different operations have been flow charted.

1. Pair Selection (Altitude Filter)
2. Altitude Test (for Mode C only)
3. Gross Range Filter
4. Convergence/Divergence Filter (Relative Motion)
5. Closest Approach Test
6. Extrapolation

7.1.2.1 Pair Selection (Altitude Filtering)

The Pair Selection involves the selection of aircraft pairs from the same altitude level of the Segregated Altitude Table (SAT). The benefits derived from this method of pair selection have been pointed out in Section 5.0 and Appendix A; namely, it assures a selection of aircraft pairs which either violate vertical separation standards at the present time or

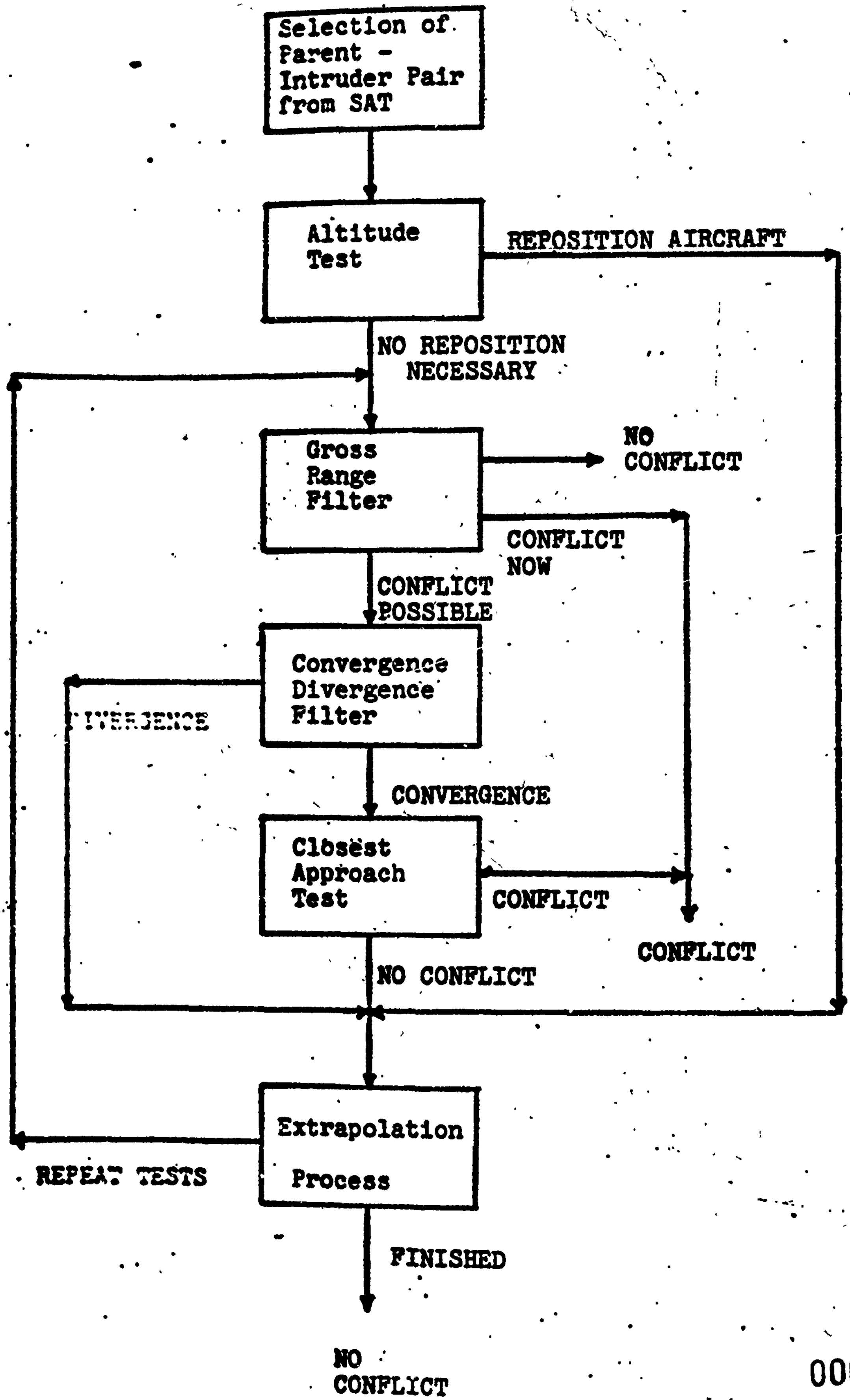

Figure 7.3 Radar Functional Flow

are likely to do so as the result of an altitude maneuver. It provides a means of filtering out those aircraft pair combinations which have and are maintaining vertical separation standards.

7.1.2.2 Altitude Test

Upon the selection of an aircraft pair a check is made to determine if either aircraft is in an altitude change. If both are in level flight process control passes to the Gross Range Filter discussed in Section 7.1.2.3. If either aircraft is changing altitude and is not Mode C equipped, the pair will not be processed. This decision is based on the lack of data for these aircraft. The altitude at the time of processing is not known and only a nominal altitude change rate for aircraft type is known. With this uncertainty of vertical position and velocity, conflicts cannot be accurately predicted.

When one or both aircraft is making an altitude change and is Mode C equipped there is a period of interest for the pair determined by the time their vertical separation is less than the required minimum. This time period is described in more detail in Section 7.3.3 (Altitude Maneuver Processing). If this period of interest terminates before the Conflict Search Interval (CSI) used by the Extrapolation Process, the CSI is set to this earlier time. If the period

of interest starts at a time later than the present time, process control is transferred to the Extrapolation Process (Section 7.1.2.6), to update the aircrafts' positions to the beginning of this period.

7.1.2.3 Gross Range Filter

The Gross Range Filter, described in Section 6.2, will calculate the separation distance between the two aircraft to determine if the pair could possibly conflict in the remaining look ahead time period. The Gross Range Filter will have three possible exit points.

1. If the aircraft pair are sufficiently far apart that they cannot conflict in the remaining ~~portion of the Conflict Search~~ Interval, the Gross Range Filter will terminate the conflict prediction process for this aircraft pair.
2. If the aircraft pair are so close together that they violate separation standards at the present time, a conflict has been detected and processing is complete for this pair.
3. If neither of the above occur, the process control will pass to the next filter separation.

7.1.2.4 Convergence/Divergence Filter (Relative Motion)

The Convergence/Divergence Filter, described in Section 6.3, will determine the relative motion of one aircraft with respect to the other. This filter will have two possible exit points.

1. If the aircraft pair are diverging or are maintaining present separation, the filter will terminate processing of this route segment and transfer process control to the Extrapolation Process (Section 7.1.2.6).

2. If the aircraft pair are converging, the filter will transfer process control to the Closest Approach Test (Section 7.1.2.5) for more detailed processing.

7.1.2.5 Closest Approach Test

The function of the Closest Approach Test is to determine if the intruder aircraft will violate the horizontal separation requirement of the parent aircraft. As stated in Section 7.1.1, the intent of Conflict Prediction radar processing is to protect a circle (in the XY plane) centered about the parent aircraft (see Figure 7.4). The radius of the protected circle is defined as follows:

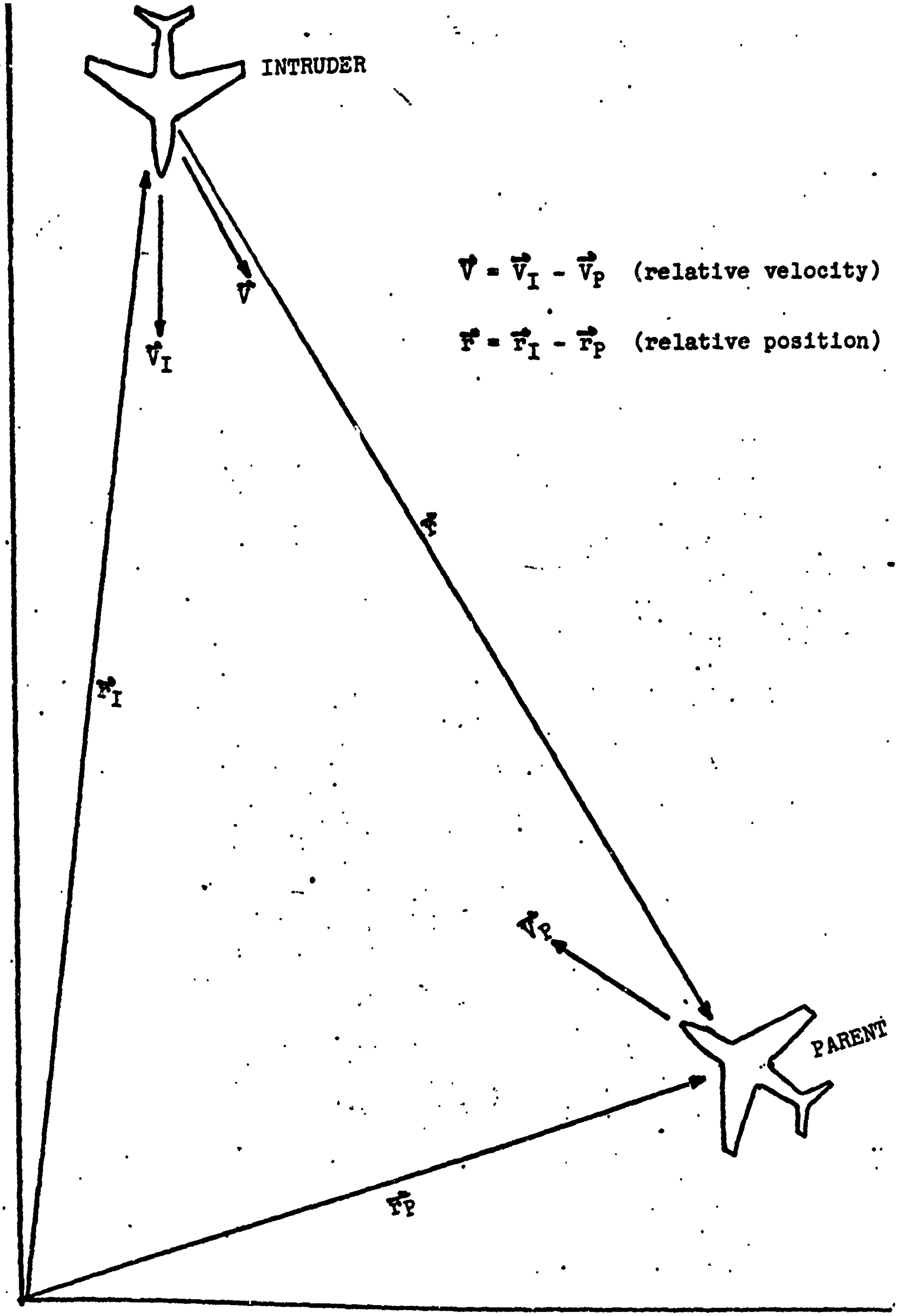

Figure 7.4.a Closest Approach Test

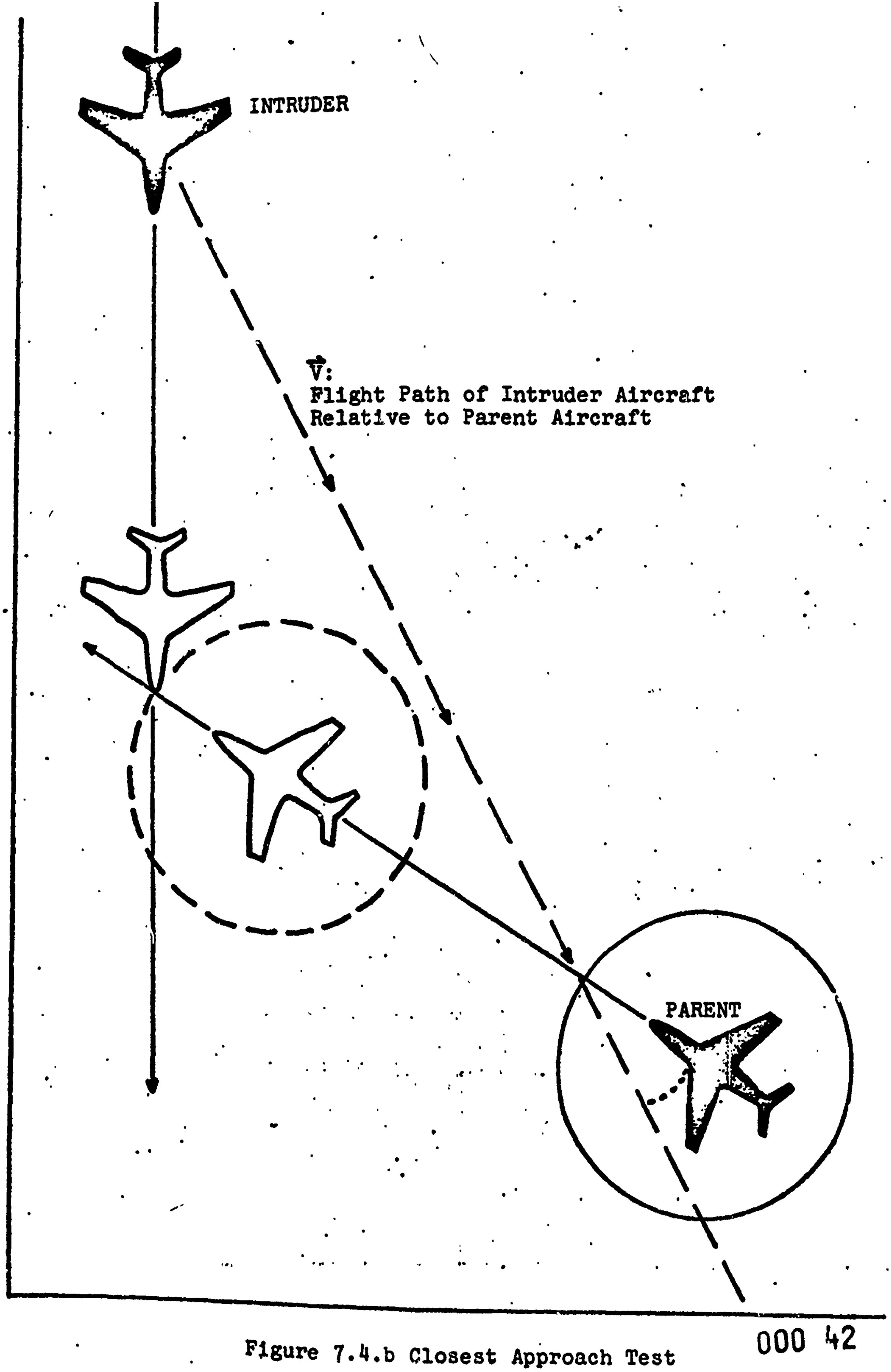

Figure 7.4.b Closest Approach Test

1. If the present position of both aircraft are within 40 miles of a radar antenna site, and if the extrapolated positions of the parent/intruder pair are within 40 miles of a radar antenna site at the time of their closest approach, and if neither aircraft is in FLAT COAST nor FREE COAST tracking mode, then a 3(1-10,1) mile separation requirement will be imposed.

2. If all of the above conditions are not met, a 5(1-15,1) mile separation will be required.

The first calculation done by the Closest Approach Test will be to compute the time of closest approach of the aircraft pair. The time of closest approach is derived by taking the time derivative of the following equation:

$$\vec{r} = \vec{r}_0 + \vec{V}t \qquad \text{(where r is the relative position vector)}$$

$$r^2 = \vec{r}\cdot\vec{r} = r_0{}^2 + 2\vec{r}_0\cdot\vec{V}t + V^2t^2$$

$$2r\frac{dr}{dt} = 2\vec{r}_0\cdot\vec{V} + 2V^2t$$

Setting $\frac{dr}{dt} = 0$, t becomes the time of closest approach (t_{ca}):

$$t_{ca} = -\frac{\vec{r}_0\cdot\vec{V}}{V^2}$$

When t_{ca} is substituted into the original equation, r becomes the distance of closest approach (r_{ca}):

$$r_{ca}^2 = r_0^2 - \frac{(\vec{r}_0 \cdot \vec{V})^2}{V^2}$$

If the radius of the protected circle about the parent is defined as the value r_m, the Closest Approach Test will consider the aircraft pair to be in violation of separation standards if $r_{ca} \leq r_m$.

Should the Closest Approach Test indicate that a conflict does exist, the start time and end time of violations may be obtained by computing the times at which the intruder will break the protected circle about the parent. This may be done by setting $r = r_m$ in the original equation, yielding

$$0 = r_0^2 - r_m^2 + 2\vec{r}_0 \cdot \vec{V}t + V^2t^2$$

Solving for t, we have:

$$t = -\frac{\vec{r}_0 \cdot \vec{V}}{V^2} \pm \frac{\sqrt{(\vec{r}_0 \cdot \vec{V})^2 - V^2(r_0^2 - r_m^2)}}{V^2}$$

$$\text{or} \quad t = t_{ca} \pm \frac{1}{V}\sqrt{\frac{(\vec{r}_0 \cdot \vec{V})^2}{V^2} - r_0^2 + r_m^2}$$

Since, at the time of closest approach: $r_{ca}^2 = r_0^2 - \frac{(\vec{r}_0 \cdot \vec{V})^2}{V^2}$ the equation becomes

$$t = t_{ca} \pm \frac{1}{V}\sqrt{r_m^2 - r_{ca}^2}$$

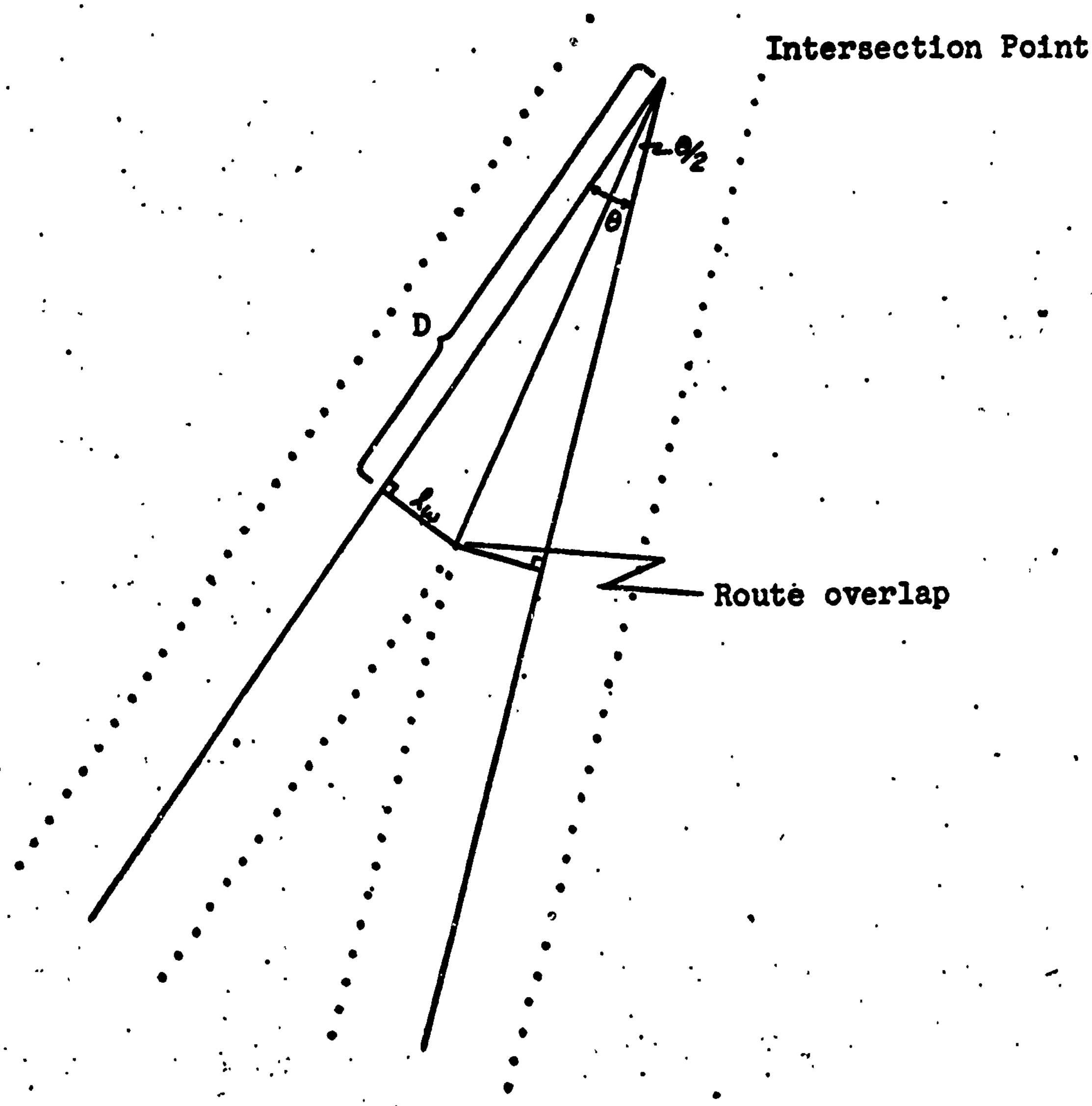

Figure 7.10

Small Angle Intersection

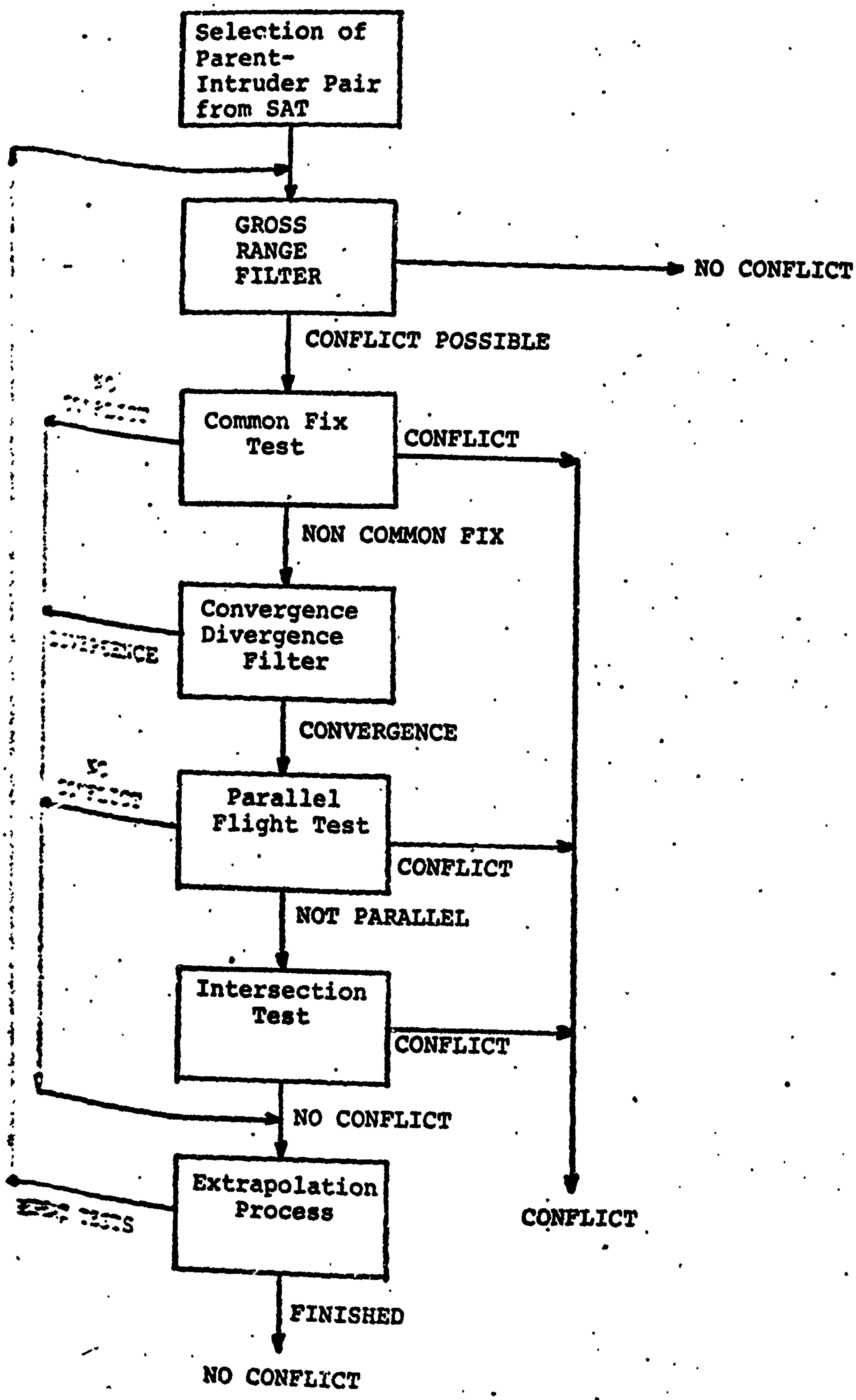

Figure 7.6 Non-Radar Functional Flow

When a violation of radar separation standards is predicted, the time at which the predicted conflict will occur must be further examined. If the conflict exists within the time span of the route segment being conflict checked, then the aircraft pair are considered to be in violation of horizontal separation standards. If the conflict does not exist within the time span of the route segment checked, then the conflict is voided. Three different situations may produce a voided conflict:

1. either aircraft is scheduled to execute a turn maneuver prior to the start time of the conflict;
2. either aircraft is scheduled to reach its last fix prior to the start time of the conflict;
3. the start of conflict lies beyond the search time limit imposed by the Conflict Search Interval.

If the conflict is voided, then process control will be transferred to the Extrapolation Process (Section 7.1.2.6).

A detailed scheme for programming these equations may be found in the Detailed Computation Flow Chart diagrammed in the paper titled "A Proposed Conflict Prediction Scheme for the NAS Stage A Program Environment" by Davis and Kirchoff.

7.1.2.6 Extrapolation Process

The Extrapolation Process will control the route segment processing loop. The Extrapolation Process will have three possible exit points.

1. If the position of either aircraft has been extrapolated to its last fix, or if the route extrapolation process has exceeded the Conflict Search Interval (CSI), the Extrapolation Process will terminate conflict checking for this aircraft pair. The pair will be considered conflict free.

2. If process control comes from the Altitude Test the Extrapolation Process will:

   - extrapolate the position of the aircraft pair to the time of interest as defined by the altitude change. (See Section 7.3.3 for details of this time of interest),
   - access the new heading data if a fix is reached in the position extrapolation process so that new velocity components may be computed,

- transfer process control to the Gross Range Filter operation to initiate conflict checking, unless position extrapolation went beyond the last fix of either aircraft. In this case the pair is conflict free and conflict checking is terminated.

3. If neither of the above requirements are satisfied, the Extrapolation Process will:
   - extrapolate the position of the aircraft pair to the CTA of the nearest* fix where a change in aircraft heading will be required,
   - access the new heading data for the aircraft arriving at the fix so that new velocity components may be computed,
   - reduce the look ahead time interval by the number of minutes of route segments which have been conflict checked thus far, and
   - transfer process control to the Gross Range Filter operation to initiate conflict checking of the new route segment.

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* "Nearest" in this instance refers to nearest in terms of flight time, not distance.

7.1.3 FLAT Track vs. FLAT Track

The processing of two aircraft which have FLAT and/or FLAT COAST tracking modes will be accomplished as outlined in Section 7.1.2. The Conflict Search Interval will be a 10 (5-30,1) minute look ahead period. The processing of FLAT TURN tracks will be discussed in Section 7.3.4 (Special Cases).

7.1.4 FLAT Track Vs. FREE Track

The processing of aircraft when one is FLAT or FLAT COAST and the other FREE or FREE COAST will be accomplished as outlined in Section 7.1.2 with the exception that, for the FREE/FREE COAST track, no route extrapolation will be done. The flight path of the FREE tracked aircraft will be projected as a straight line without any turn point. Since the intended flight path of a FREE track is not known, a shortened Conflict Search Interval of 4 (1-10,1) minutes will be used. The processing of FLAT TURN tracks will be discussed in Section 7.3.4 (Special Cases).

7.1.5 FREE Track Vs. FREE Track

The processing of two aircraft which have FREE/FREE COAST tracking modes will be accomplished as outlined in Section 7.1.2 with the exception that no route extrapolation will be done. The flight paths of both aircraft will be

projected as straight lines without any turn points. Since the intended flight paths of the aircraft are not known, the shorter Conflict Search Interval of 4 (1-10,1) minutes will be used.

7.2 Non-Radar Aircraft

There are some geographic areas that do not have radar coverage. In these areas IFR aircraft fly under different separation rules then in radar covered areas. These aircraft will be conflict checked in level flight. However, insufficient data makes accurate prediction of conflicts during an altitude change impossible.

7.2.1 Non-Radar Separation Standards

The standards for separation of non-radar tracked IFR aircraft are specified in the excerpts from the ATC Procedures Manual (AT P7110.1B) included in Section 3.0 of this paper. The non-radar separation criteria which will be programmed are as follows:

- Vertical separation - At altitudes up to and including 29,000 feet a vertical separation of 1,000 feet will be required; above 29,000 feet, the vertical separation requirement increases to 2,000 feet.
- Lateral separation - A lateral separation of 4 (1-10,1) miles will be required on each side of the aircraft.

- Longitudinal separation - A longitudinal separation of 10 (1-20,1) minutes of flying time will be required in front of and behind the aircraft.

The above requirements will be applied to both aircraft while the pair is being conflict checked.

The resulting effect of the above interpretation of non-radar separation standards is as follows: When Conflict Prediction checks a specific aircraft pair for a potential separation violation, the airspace about both aircraft will be protected from overlap situations. The protected airspace about an aircraft is essentially a box in shape - a rectangular area whose size is a function of the velocity of the aircraft. A pictorial representation of the non-radar protected airspace is shown in Figure 7.5.

7.2.2 Programming Technique

To describe the Conflict Prediction process, consider the processing in terms of a pair of non-radar aircraft which are adhering to their respective flight plans. In the first place, any pair of aircraft processed will have been chosen from the same altitude level of the Segregated Altitude Table (SAT). This implies that most pairs violate vertical IFR separation standards. The exception will occur when the aircraft are not flying at cardinal altitudes. (See Appendix B for further details).

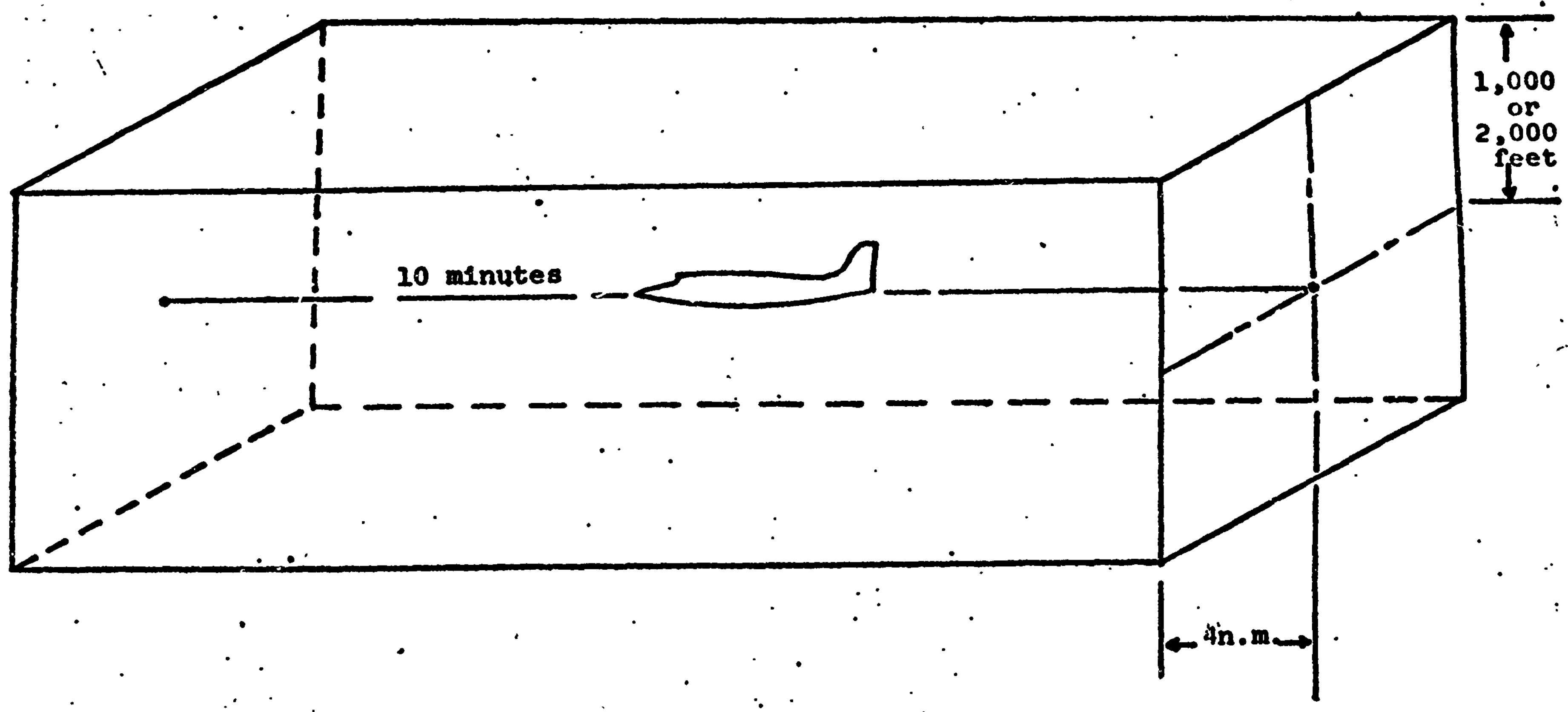

Figure 7.5 Non Radar Protected Airspace

Hence, the use of the SAT reduces the conflict prediction problem to a two dimensional question: do the aircraft pair also violate horizontal IFR separation standards?

The general approach used to answer this question can be described by use of figure 7.2. Starting with the flight plan positions of aircraft A and aircraft B at the present time (t_0), the aircraft flight paths will be projected to their next respective fixes using a two dimensional, straight line, constant velocity extrapolation of position. The flight paths of aircraft A and B will then be examined in the time period $t_0 - t_1$ (where t_1 is the CTA of the nearest* fix) to determine if a conflict situation will occur. If a conflict does not occur, the aircraft positions will then be extrapolated to time t_1, the new heading data for the second route leg of aircraft A will be acquired, and the flight path examination repeated for time period $t_1 - t_2$ (where time t_2 again represents the CTA of the fix nearest to the present extrapolated positions of the aircraft). This process will be reiterated until either:

1. aircraft A or aircraft B arrives at its last fix,
2. The total time of route projections exceeds the time limit specified for the Conflict Search Interval (CSI), or
3. a conflict is detected.

* "Nearest" in this usage refers to nearest in terms of flight time, not distance

A detailed scheme for programming the non-radar Conflict Prediction may be found in the Detailed Computation Flow Chart diagrammed in the paper titled "A Proposed Conflict Prediction Scheme for the NAS Stage A Program Environment" by Davis and Kirchoff.

The implementation of this approach to conflict prediction processing, along with the application of the process filters described in Section 6.0, is diagrammed in the functional flow chart shown in Figure 7.6. Seven different operations have been flow charted.

1. Pair Selection (Altitude Filter)
2. Gross Range Filter
3. Common Fix Test
4. Convergence/Divergence Filter (Relative Motion)
5. Parallel Flight Test
6. Intersection Test
7. Extrapolation Process

7.2.2.1 Pair Section (Altitude Filtering)

The Pair Selection involves the selection of aircraft pairs from the same altitude level of the Segregated Altitude Table (SAT). The benefits derived from this method of pair selection have been pointed out in Section 5.0 and Appendix A; namely, it provides a means of filtering out most aircraft pair combinations which have and are maintaining vertical separation standards.

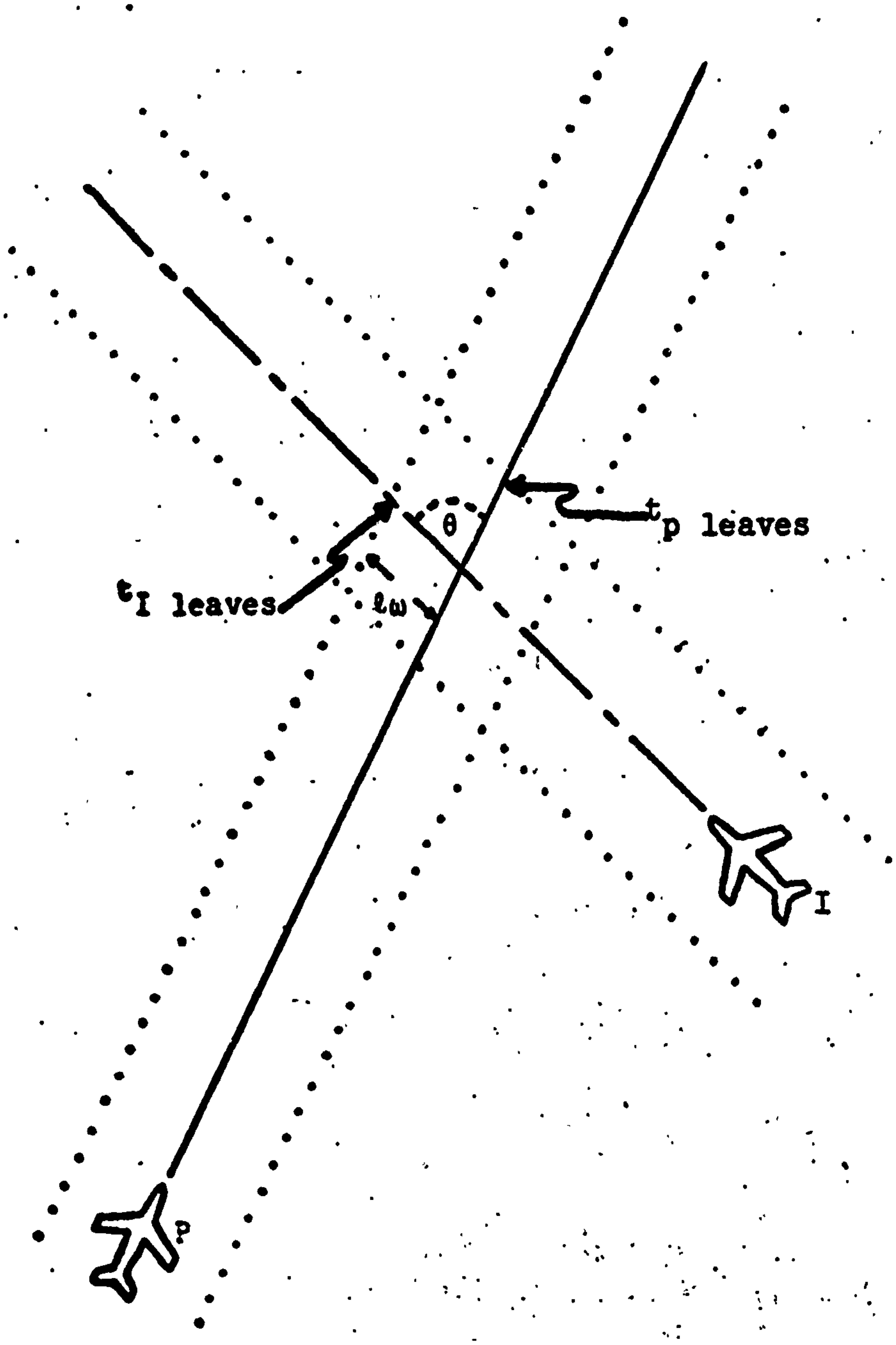

Figure 7.8

Intersection Test

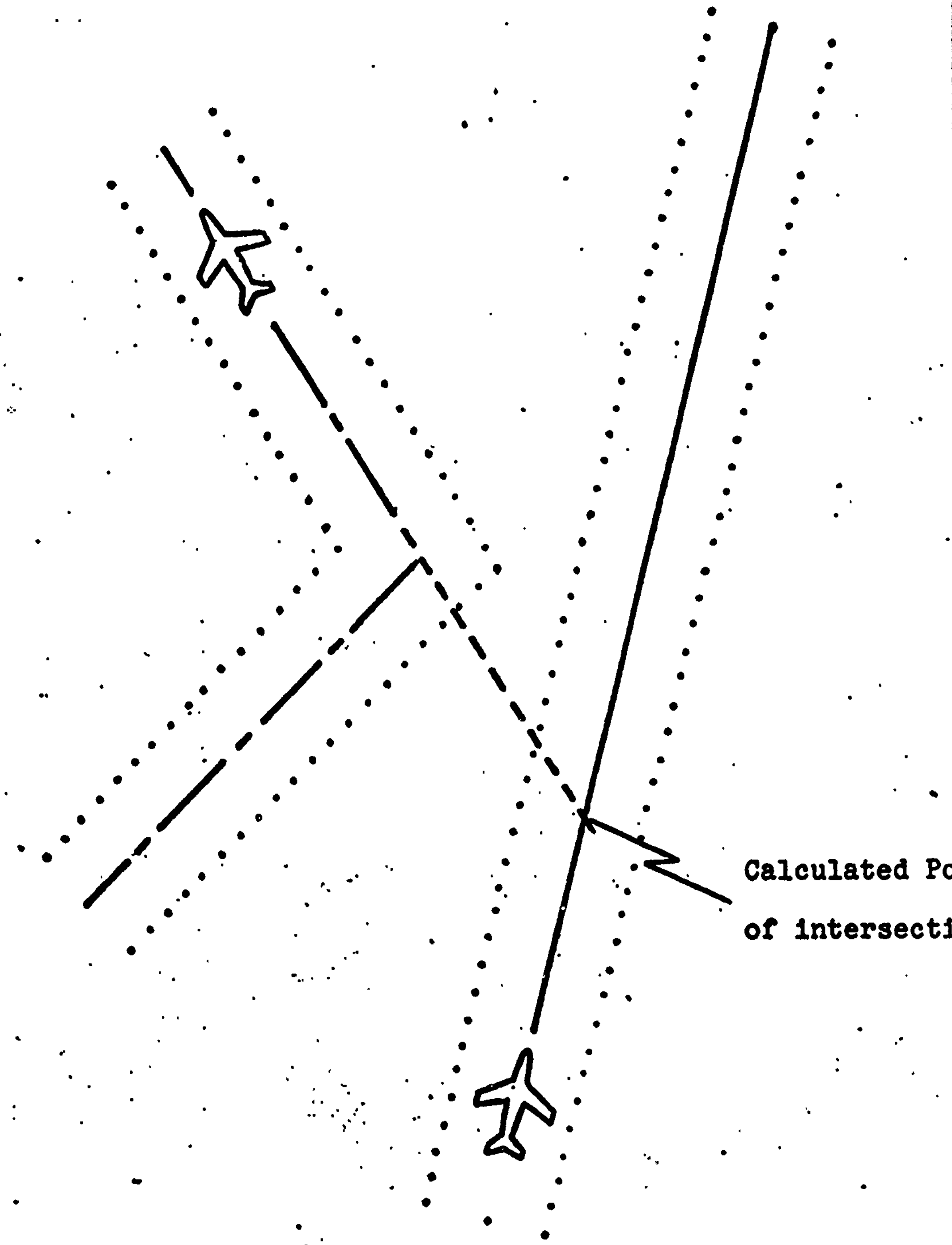

Figure 7.9

Avoiding False Conflicts

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7.2.2.2 Gross Range Filter

The Gross Range Filter, described in Section 6.2, will calculate the separation distance between the two aircraft to determine if the pair could possibly conflict in the remaining look ahead time period. The Gross Range Filter will have two possible exit points.

1. If the aircraft pair are sufficiently far apart that they can not conflict in the remaining portion of the Conflict Search Interval, the Gross Range Filter will terminate the conflict prediction process for this aircraft pair.
2. Otherwise, the process control will pass to the Common Fix Test (Section 7.2.2.3) or the Convergence-Divergence Filter (Section 7.2.2.4).

7.2.2.3 Common Fix Test

The Common Fix Test is used for those pairs of aircraft with a known point of route intersection (fix) and known time of intersections (CTA's). Tests are made to determine if the horizontal protected airspace of the intruder does or will overlap the horizontal protected airspace of the parent. The protected airspace is defined as follows:

- A 4 (1-10,1) mile wide area on either side of the aircraft (lateral separation) for a length in front and behind equal to the distance flown in 10 (1-20,1) minutes (longitudinal separation).

Aircraft heading toward the same fix must have the required longitudinal separation at the fix. This is determined by comparing their CTA's. If they also have the same heading angle, the aircraft farther from the fix must have the later CTA to insure that an overtake situation does not occur.

Another situation requiring special consideration could occur and that is if the heading angle difference is less than 15°. Since the overlap of the protected areas is so long in this case more than just longitudinal separation at the fix is required. This case will be discussed in detail later in this section.

7.2.2.4 Convergence/Divergence Filter (Relative Motion)

The Convergence/Divergence Filter, described in Section 6.3, will determine the relative motion of one aircraft with respect to the other. This filter will have two possible exit points.

1. If the aircraft pair are diverging or are maintaining present separation, the filter will terminate processing of this route segment and transfer process control to the Extrapolation Process (Section 7.2.2.7)
2. If the aircraft pair are converging, the filter will transfer process control to the Parallel Flight Test (Section 7.2.2.5) or the Intersection

Test (Section 7.2.2.6) for more detailed processing.

7.2.2.5 Parallel Flight Test

The Parallel Flight test is used for those aircraft pairs having equal or opposite heading angles.

The first test is to determine if the pair of aircraft have lateral separation. This can be determined by calculating the following vector equation. (See figure 7.7)

$$A = \left| \bar{r} \cdot \bar{V}_p \times \hat{k} \right|$$

A is the magnitude of the component of r perpendicular to the path of the parent aircraft P times the velocity of P. Comparing A to twice the lateral separation times V_p will establish whether the pair have lateral separation. If lateral separation exists, it exists for the entire route segment and processing is passed to the Extrapolation Process (Section 7.2.2.7). Where lateral separation does not exist, longitudinal separation must or the pair will not be conflict free.

To determine if longitudinal separation exists, the distance between the aircraft must be known. Their time separation can then be calculated and compared with the separation minimum. Since lateral separation does not exist it can be considered to be zero, reducing the situation to a one dimensional problem. Hence, the distance required, R, can be obtained as follows: (See figure 7.7)

$$R = \frac{\bar{r} \cdot \bar{V}_p}{V_p}$$

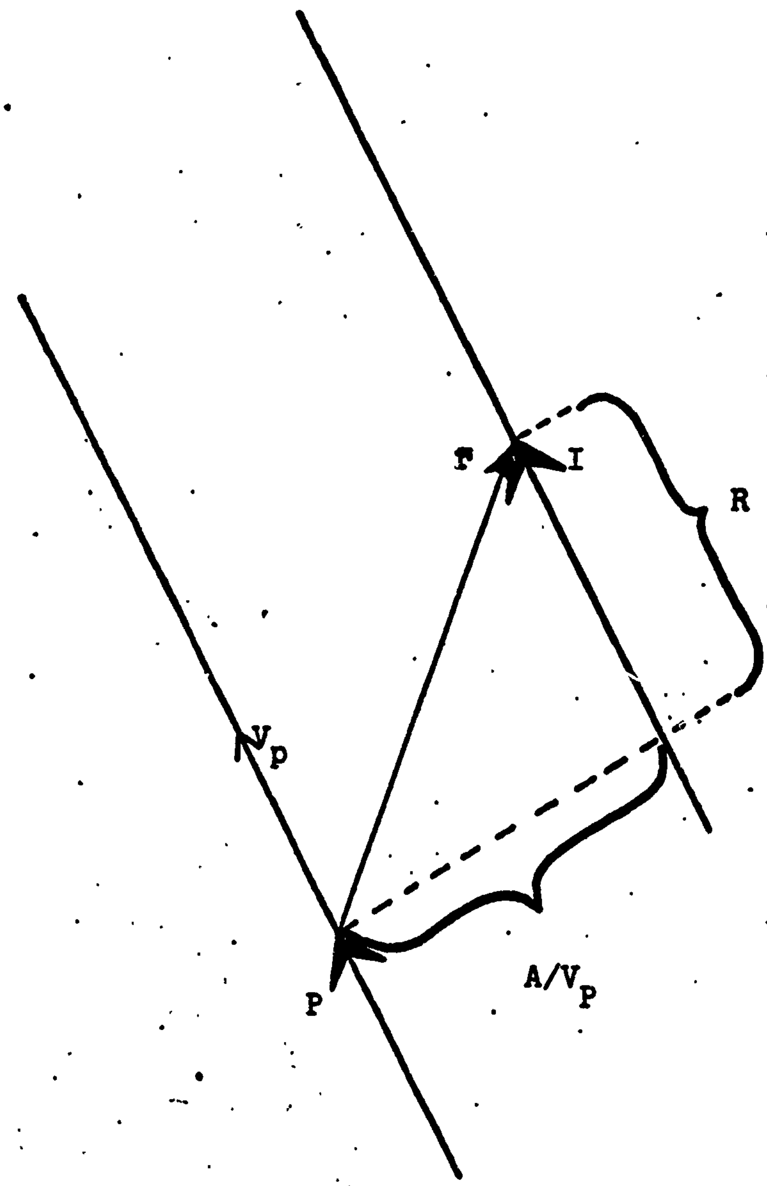


Figure 7.7 Parallel Flight.

With the distance information calculated, the separation in time can be obtained by dividing by the appropriate velocity for the particular situation. When a conflict is predicted it may be voided by one of the following:

- o one of the aircraft is scheduled to change course prior to the start of the predicted conflict;
- o one of the aircraft is scheduled to terminate his flight before the predicted conflict;
- o the start of the conflict lies beyond the search time limit imposed by the Conflict Search Interval.

If the conflict is voided, process control will be transferred to the Extrapolation Process (Section 7.2.2.7). If the conflict was not voided, control is transferred to the message output process (Section 8.0) and then back to pair selection (Section 7.2.2.1).

7.2.2.6 Intersection Test

The function of the Intersection Test is to determine if the horizontal protected airspace of the intruder aircraft does or will overlap the protected airspace of the parent.

The first information calculated is the time each aircraft reaches the intersection point of their current routes.

$$t_I = \frac{\vec{r} \cdot \vec{V}_p \times \hat{k}}{\vec{V}_p \cdot \vec{V}_I \times \hat{k}}$$ intersection time of intruder

$$t_p = \frac{\vec{r} \cdot \vec{V}_I \times \hat{k}}{\vec{V}_p \cdot \vec{V}_I \times \hat{k}}$$ intersection time of parent

Aircraft whose routes intersect at less than 15° will be discussed later. The following deals with intersections 15° or larger. At the point of intersection, longitudinal separation must be maintained. In an intersection situation this separation is defined between the time the first aircraft leaves the route width of the second and the time the second reaches the intersection. The first aircraft is defined as the aircraft that reaches the intersection first. The times that the aircraft leaves the route width of the other is calculated as follows:

$$t_I \text{ leaves} = t_I + \frac{\ell\omega}{V_I \sin\theta}$$

$$t_p \text{ leaves} = t_p + \frac{\ell\omega}{V_p \sin\theta}$$

where $\ell\omega$ = the lateral separation standard and

θ = the angle between the routes

(See figure 7.8)

To eliminate obvious false conflicts as pictured in figure 7.9 and to reduce the number of past conflicts predicted, the following test is made. If either or both aircraft are currently beyond the route width of the other, i.e., t_I leaves and/or t_p leaves are negative, process control is transferred to the Extrapolation process (Section 7.2.2.7).

Other situations that transfer control to the Extrapolation process are:

$$D = \frac{2\ell\omega}{\theta}$$

This approximation results in a time error of about 5.4 seconds when $\ell\omega = 4$ miles for an aircraft flying 120 m.p.h. The error is reduced as the speed of the aircraft increases or as the angle decreases.

Once the area of overlap is defined, the time span that each aircraft will be in this area can be found from the distance D, the aircraft velocity, and the time of intersection (either calculated or CTA).

During this overlap time period the aircraft may be considered as parallel flights and are processed in a similar manner. A detailed flow of this process can be found in "A Proposed Conflict Prediction Scheme for the NAS Stage A Program Environment" by Davis and Kirchoff.

7.2.2.7 Extrapolation Process

The Extrapolation Process will control the route segment processing loop. The Extrapolation Process will have two possible exit points.

1. If the position of either aircraft has been extrapolated to its last fix, or if the route extrapolation process has exceeded the Conflict Search Interval (CSI), the Extrapolation Process will terminate conflict checking for this aircraft pair. The pair will be considered

- no conflict found;
- a flight plan predicted turn occurs before the intersection with the route of the aircraft.

If a conflict is predicted but separation will not be broken in the remaining Conflict Search Interval the conflict is voided and control passes to Pair Selection (Section 7.2.2.1).

For routes with closing angles of less then 15°, longitudinal separation at the intersection is necessary. However, it is not sufficient. An overtake possibility could exist in the region where the routes' widths overlap (See. figure 7.10).

The overlap point is obtained from the isosceles triangle formed by the intersection point and the route legs from this point to the overlap of the routes and a line drawn through the overlap point. The distance along each aircraft's route from the intersection point is calculated as follows:

$$D = \frac{\ell\omega}{\tan \theta/2}$$

where D = distance along route from the intersection to where overlap occurs.

θ = angle between aircraft routes

$\ell\omega$ = lateral separation standard

For small angles, the tangent can be approximated by the angle itself in radians.

Hence:

conflict free.

2. If neither of the above requirements are satisfied, the Extrapolation Process will:

   o extrapolate the position of the aircraft pair to the CTA of the nearest* fix where a change in aircraft heading will occur,

   o access the new heading data for the aircraft arriving at the fix so that new velocity components may be computed,

   o reduce the look ahead time interval by the number of minutes of route segments which have been conflict checked thus far, and

   o transfer process control to the Gross Range Filter operation to initiate conflict checking of the new route segment.

7.2.3 Non-Radar vs Non-Radar

The processing of two aircraft that do not have radar coverage will be accomplished as outlined in Section 7.2.2. The Conflict Search Interval will be a 20 (10-30,1) minute look ahead period.

7.2.4 Non-Radar vs FLAT Track

The processing of aircraft when one is FLAT or FLAT COAST and the other is Non-Radar will be accomplished as outlined in

*"Nearest" in this instance refers to nearest in terms of flight time, not distance.

Section 7.2.2. The Conflict Search Interval will be a 20 (10-30, 1) minute look ahead period. The processing of FLAT TURN tracks will be discussed in Section 7.3.4 (Special Cases).

7.2.5 Non-Radar vs. FREE Track

The processing of one aircraft that is FREE tracked and one that is Non-Radar will be accomplished as outlined in Section 7.2.2, with the exception that no route extrapolation will be done for the FREE tracked aircraft. His current heading will used as his heading for the entire Conflict Search Interval. Since the intent of the FREE tracked aircraft is not known, a shortened Conflict Search Interval of 4(1-10,1) minutes will be used.

7.3 Special Cases

The previous sections of this paper presented the algorithms which will be applied in the general case of the conflict checking process. This section discusses other situations which will occur in the enroute environment and require special handling by Conflict Prediction.

7.3.1 Hold Processing

Aircraft in a hold status will be conflict checked. The algorithm used by Conflict Prediction in this instance will protect a circular area (centered at the holding fix) from all other active IFR flights in the system (see figure 7.11). The radius of the circular area (R) will be defined as the sum

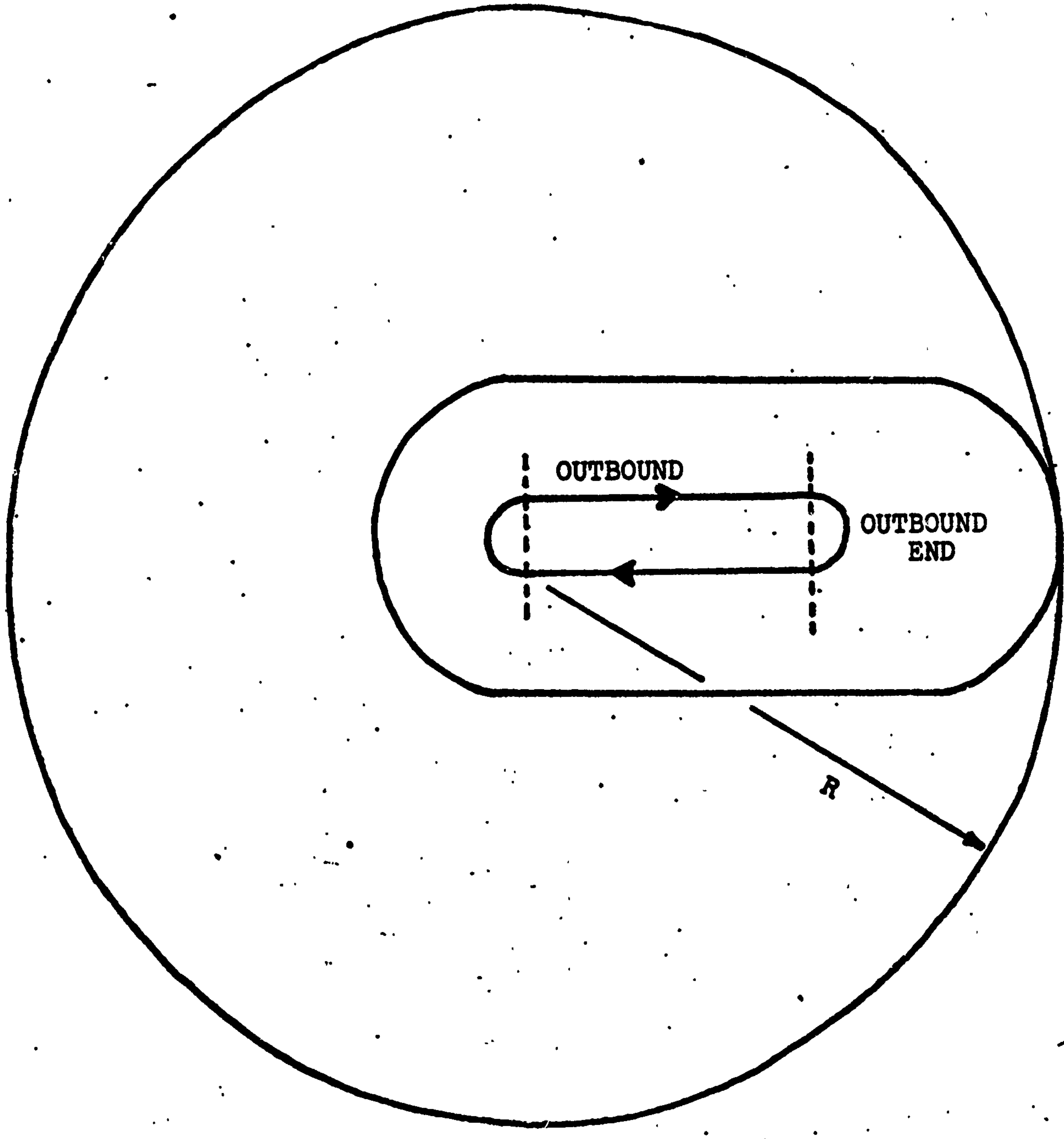


Figure 7.11 Hold Protected Airspace

of the following four components:

1. the outbound leg distance,
2. the distance from the end of the outbound leg to the outbound end of the holding pattern,
3. an overfly error distance of 1/2 minute on the outbound leg, and
4. a four mile lateral separation distance about the aircraft.

At 14,000 feet and below, the radius of the circular area will be defined assuming an aircraft flying a one minute outbound leg at 210 knots. This assumption indicates that the radius of the protected circle should be defined as R=11 (3-20,1) nautical miles.

Above 14,000 feet the radius of the circular area will be defined assuming an aircraft flying a one and one-half minute outbound leg at 310 knots. This assumption indicates that the radius of the protected circle should be defined as R=16 (3-30,1) nautical miles.

In the instance of conflict checking an aircraft pair where one is in a hold status and the other is not, two separate areas must be conflict checked for separation violations: the circular area about the hold fix, and the area of lateral separation about the flight path of the aircraft not in hold status. For radar tracked aircraft, the lateral separation distance

will be defined as L=0 (0-15,1) nautical miles. For non-radar tracked aircraft, the lateral separation distance will be defined as L=4 (1-10,1) nautical miles. The algorithm used to conflict check these two areas is as follows:

1. The area of protection about the hold fix will be increased to include the lateral separation requirement of the aircraft not in hold, producing a circular area of protection with a radius R' = R+L.
2. The aircraft not in hold status will be projected along its flight path using a two-dimensional, straight line extrapolation of position.
3. If the projected flight path breaks the circle of protection about the fix, the aircraft will be considered to be in conflict.

In the instance where both aircraft being conflict checked are in hold status, Conflict Prediction will test to determine if the two circles of protection overlap. If an overlap occurs, the aircraft will be considered to be in conflict.

7.3.2 Mode C Altitude Data

The most accurate altitude data available in NAS is that from the Mode C transponder. This is mainly true due to the fact it is automatically updated each radar scan. Since the time lag in obtaining current altitude information is small,

it is only natural to assume that mode C data would be the best data on which to base Conflict Prediction processing.

Since three dimensional radar does not exist in NAS, a velocity component in the Z-direction is not calculated as x and y components are. One possible method might be to use a history of mode C altitude returns to establish a z velocity component ($\dot{z}$). An accurate z velocity would greatly reduce the uncertainties in conflict prediction of aircraft in altitude maneuvers. A method of determing $\dot{z}$ is contained in Appendix D. Using this method, with the current accuracy of mode C data being $\pm$ 100 feet, eight observations are required to obtain $\dot{z}$ to an accuracy of $\pm$ 100 feet/min. or five observations for an accuracy of $\pm$ 200 feet/min. For 100 feet/min. accuracy, an aircraft with a $\dot{z}$ of 2000 feet/min. would change altitude by over 2300 feet before the $\dot{z}$ data became available. These figures indicate a need for more accurate z data or a faster method of obtaining $\dot{z}$.

Assuming that a reasonably accurate $\dot{z}$ can be acquired or calculated quickly, a Conflict Prediction Scheme exists for processing aircraft in an altitude change. This scheme is discussed in Section 7.3.3.

7.3.3 Altitude Maneuver Processing

The fact that an accurate altitude rate of change is not immediately available led to the following scheme for processing

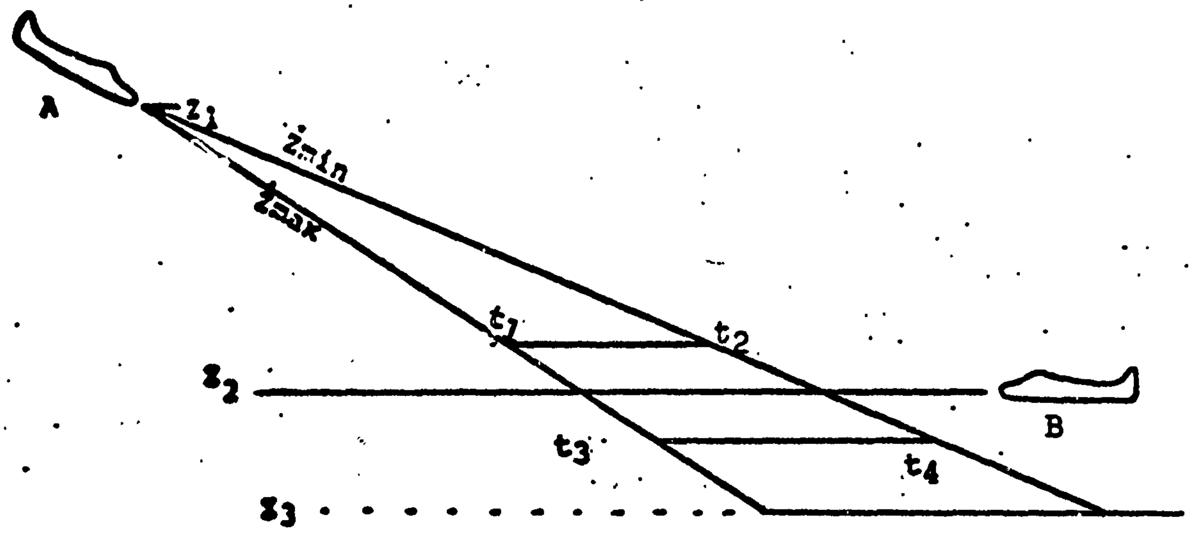
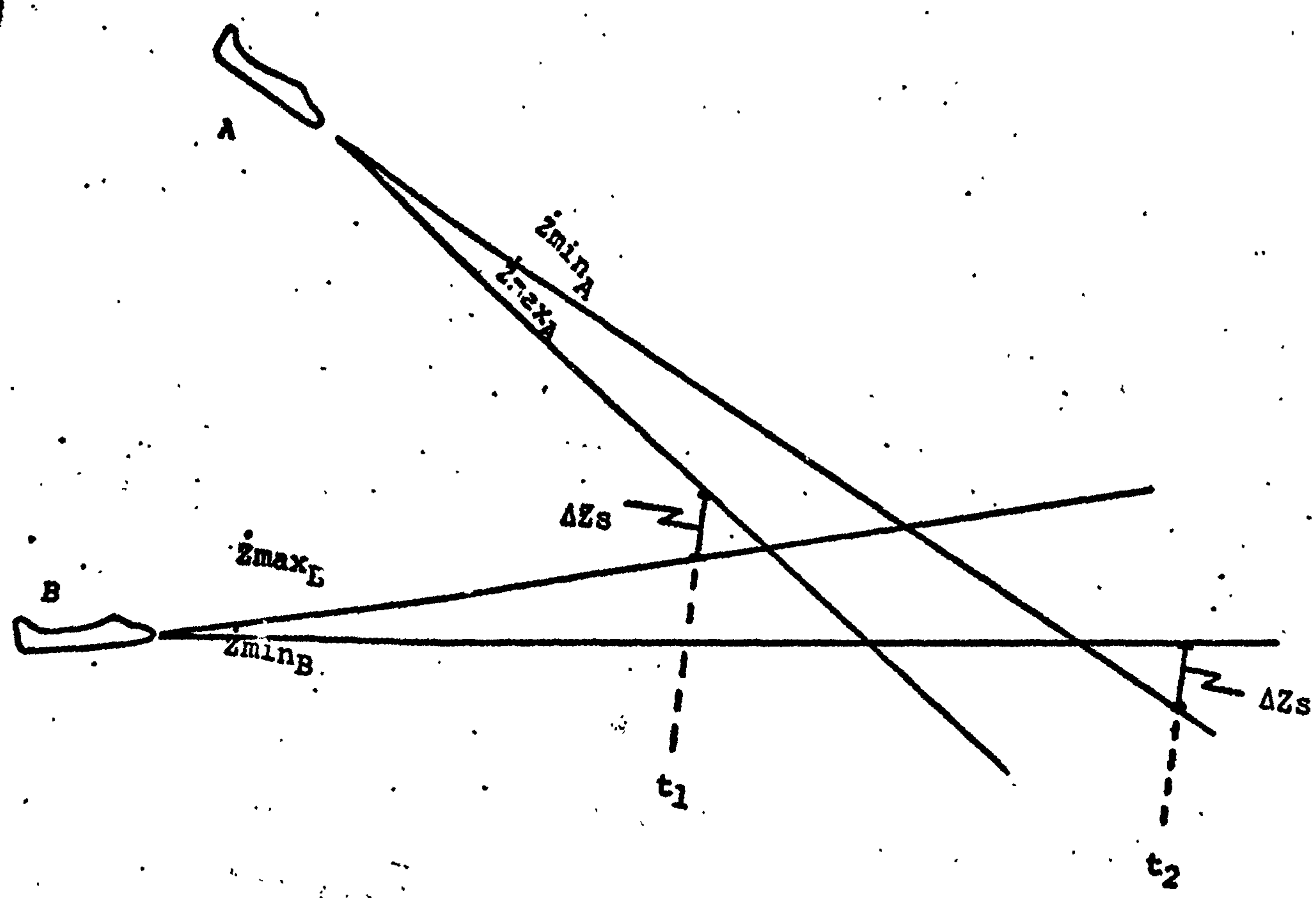


Figure 7.12

Conflict Predicting During Altitude Change

missing a conflict it must be assumed that vertical separation is violated between t_1 and t_4. Based on the assumption of a constant horizontal velocity the position of aircraft A in the horizontal plane will be known as a function of time, independent of $\dot{z}$. Therefore, the problem is reduced to that of two aircraft in level flight between t_1 and t_4 and can be processed by the method described in the radar tracked aircraft programming technique, (Section 7.1.2). There is, of course, special consideration necessary for final altitudes within the vertical separation bounds of aircraft B.

Case 2- Aircraft B in an altitude change at z_2 feet, (Figure 7.13). Due to the compounding effect of the uncertainty of the time when the aircraft break and again obtain vertical separation when both aircraft have a $\dot{z}_{max}$ and $\dot{z}_{min} \neq 0$, accurate vertical separation prediction cannot be performed. However, to the accuracy of the $\dot{z}$ information available, a time span similar to Case 1 can be defined and the radar tracked technique (Section 7.1.2) applied to this time span. Again this span would be from the earliest possible time vertical separation could be broken, t_1, to the latest possible time separation would again be attained, t_2, as pictured in figure 7.13.



$\Delta \dot{Z}s$ = Vertical Separation Minimum

Figure 7.13
Double Altitude Change

Obviously the more accurate the $\dot{z}$ information the less chance there is of predicting false conflicts. At such time that $\dot{z}$ data is as accurate as horizontal velocity with respect to their corresponding position accuracies, extremely accurate 3-dimensional conflict prediction can be accomplished for either Case 1 or Case 2.

7.3.4 FLAT TURN Processing

Conflict Prediction is periodically checking all aircraft at a frequency less than the look ahead time. An aircraft will be conflict checked on a given route leg several times before actually traversing it. Therefore, the aircraft need not be conflict checked during the relatively short time that he is turning onto his next route leg (i.e. in FLAT TURN mode). This will eliminate the task of extrapolating a curved path when the path is not explicitly known.

7.3.5 Aircraft With No Conflict Checking

Some aircraft flights will not be processed by Conflict Prediction:

1. Aircraft that are flying in accordance with Visual Flight Rules (VFR and VFR-ON-TOP) will not be conflict checked. The NAS Model 1b system contains no data for flights of this type.

2. Aircraft which lack altitude information can not be conflict checked. Flights which do not have this data item lack sufficient information to determine if a conflict situation exists.

3. Aircraft with a DELAY track maneuver status will not be conflict checked. Aircraft in DELAY status will be assumed to be flying in accordance with Visual Flight Rules (VFR).

8.0 Conflict Prediction Displays

When Conflict Prediction calculates that a separation violation between two aircraft will occur or has occurred, the responsible sector controllers will be notified. The Plan View Display (PVD) and the Computer Readout Device (CRD) will be used to communicate the presence of the conflict situation.

8.1 CRD Displays

The CRD will be used to communicate to the D controller that a violation of radar or non-radar separation standards will occur (or has occurred) between two IFR aircraft.

CRD messages fall into two categories: separation violation messages and warning messages. A separation violation message will be generated when it has been definitely established that an aircraft pair is/will be violating the separation standard criteria. A warning message will be generated when an accurate projection of the aircraft's position cannot be made (i.e. when both aircraft are in the process of an altitude change.

The conflict messages, which are to be displayed in the computer originated message area of the CRD, will contain eight fields.

1. Message identifier - first word of the message; either "CONFLICT" or "WARNING".

2. Time of violation - four numeric characters, expressed in hours (00-23) and minutes (00-59) past midnight. If a potential violation is detected, the time at which the violation will occur is output. If the violation has already occurred, the word "NOW" will be output.

3. Present separation - three numeric characters, expressed in nautical miles, indicating the relative separation of the aircraft pair at the present time.

4. Radar/non-radar indicator - one alphabetic character, either "R" or "N". The letter "R" will be used when both aircraft are radar covered. The letter "N" is used when one or both aircraft are non-radar.

5. Computer identification - three numeric characters, indicating the computer identification of each of the aircraft.

6. Aircraft identification - a maximum of seven and a minimum of two alphanumeric characters. The aircraft call signs will be used to identify each of the aircraft pair.

7. Speed - four numeric characters, expressed in knots, indicating the speed of each of the aircraft pair.

8. Altitude - three numeric characters, expressed in hundreds of feet, indicating the altitude for each of the aircraft pair at which there is/will be a violation.

The following example depicts the format in which conflict messages will be displayed on the CRD. The data to be displayed is:

Message Indicator:	CONFLICT
Time of Violation:	1457
Radar/Non-Radar Indicator:	R
Present Separation:	11
Computer Identification:	3
	7
Aircraft Identification:	EA555
	AA420
Speed:	535
	410
Altitude:	160
	165

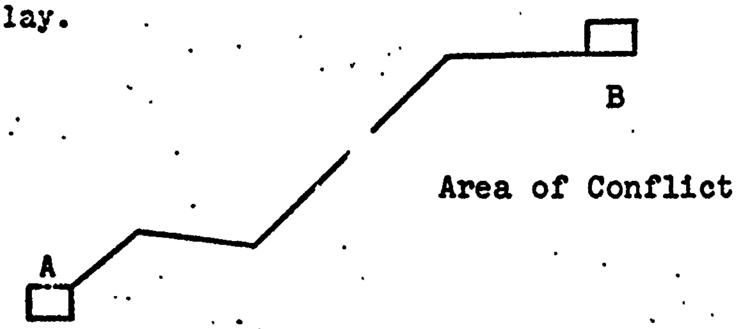
The message as it will appear on the D controller's CRD is:

```
CONFLICT 1457  R  RNG  011
003  EA555     535     160
007  AA420     410     165
```

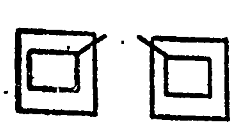
8.2 PVD Displays

The PVD will be used to communicate to the R Controller that a violation of radar separation standards will occur (or has occurred) between two radar tracked aircraft.

The PVD display used for predicted conflicts will be similar to a pair of route displays. The display will present the route of flight of each aircraft depicted by a sequence of line segments. The display will begin at the present position of the aircraft, represented by the flight plan position symbol (☐), and will terminate at the predicted point of conflict. This data will remain displayed for five seconds. The following is an example of the display.



If Conflict Prediction calculates that a violation of IFR separation standards exists at the present time, the route will be depicted as a square drawn around the flight plan position symbol of each of the aircraft. The following is an example of the display.



8.3 Multiple PVD/CRD Displays

Conflict Prediction will conflict check IFR aircraft whether they are controlled at the same or at different controller positions. If a conflict situation should arise involving more than one controller position, Conflict Prediction will take the following actions:

(1) The PVD displays for radar tracked aircraft will not be used as output to the R controllers.

(2) The CRD displays will be written as output to both D controller positions.

Table 9.1 Core Storage Estimate

			Words
I.	Data Areas		Words
	1.	FPIN - extended Table (650 entries of 2 words)	1300
	2.	SAT Index Table (50 entries of 1 word)	50
	3.	Segregated Altitude Table (750 entries of 1 word)	750
	4.	CRD Message Table (20 entries of 12 words)	240
	5.	PVD Route Display Table (20 entries of 22 words)	440
	6.	Temporary Storage	200
		Total Words	2980

			Words
II.	Program Areas*		Words
	1.	Pre-processing	450
	2.	Processing	
		a. Executive Routine	160
		b. Altitude Maneuver Processing	500
		c. Radar Processing	650
		d. Non Radar Processing	1000
		e. Hold Processing	100
		f. Extrapolation Routine	325
	3.	Output	
		a. PVD Route Display	275
		b. CRD Conflict Message	350
		Total Words	3810

III. Total Core Storage 6790 Words

handled in the system would be:

- FPIM - extended Table
- Segregated Altitude Table

The total data areas estimate is approximately 3000 words.

Program storage is based on several different methods of estimating. Pre-processing and the Executive Routine are based on an assembly language coding of the two sections. These sections include program loop control, SAT maintenance, pair selection from SAT, and switching logic. The Radar Processing figures, the Altitude Maneuver Processing figures, and the Extrapolation Routine figures are based on the core required by the Demonstration Version of Conflict Prediction in the 1b system. The output requirements are also based on the Demonstration Version program. The Non Radar Processing estimate stems from the detailed math flow of the non radar scheme. An assembly language estimate was made for each flow chart block to arrive at the estimate for the section. The total core for the program area is slightly under 4000 words.

The total core requirement is estimated to be 7000 words, with a probable range of between 6500 and 7500 words.

9.2 Processing Time Estimates

The timing estimates for Conflict Prediction are for the 1b system. Three basic limitations must be recognized re-

garding these estimates.

1. All aircraft are considered to be under radar coverage.

2. All aircraft are considered to be in level flight.

3. No wait time due to table locks etc. is considered.

One additional requirement of the system is that the distance between fixes be included and maintained in AKRR. If this is not done, the time for route extrapolation increases four fold since trigonometric calculations for next route segment would be required.

All available data was analyzed to support the assumptions used in making the timing estimates. The aircraft pair counts resulted from a 1975 expected altitude distribution (see Appendix A). Such quantities as average aircraft speed, average route segment length, average flight length, etc., utilized in the estimates are based on JAX ARTCC data.

9.2.1 Timing Equations

Support type routines' timing is based on the assembly language coding of these sections as was the core estimate. The main processing, i.e. Radar Processing and Extrapolation Routine, timings are based on the Demonstration Version of Conflict Prediction. The formula for the time required by the support routines to process all aircraft is as follows:

$$\text{Sup. Time} = 5\mu\ \text{sec.} \times \{4160 + 59\ \text{NUM} + 12\ \text{PRS}\}$$

where

NUM = the number of active aircraft.

PRS = the number of aircraft pairs

For main processing, the formula for the time to process all aircraft is:

$$\text{Proc. Time} = 5\mu\ \text{sec.} \times \{80\ \text{PRS} + 62\ \text{PRS} \times \text{GR} + \text{PRS}\ (1-\text{GR}) \times (348\ \text{RS} - 164)\}$$

where

PRS = the number of aircraft pairs.

GR = the percentage of aircraft to drop on the first pass of the filters via the Gross Range Filter.

RS = the average number of route segments processed by the program. This number is one less than the total average number of route legs traversed by each aircraft during the look ahead time period (CSI)

Both of the above formulas assume the program to be coded in assembly language. The sum of these two times, Sup. Time and Proc. Time, will be the total time required to process all aircraft. Table 9.2 shows the estimated time to process 275 aircraft for various RS and GR values. Data for the JAX 1b system was analyzed to determine the appropriate values for the Center. The values which seem to apply are GR=50% and RS=21/3, with a look ahead time of 10 minutes. The processing time for 275 aircraft would be 3.5 seconds.

9.0 Program Requirements

Various studies were made to determine the program requirements for a realistic version of Conflict Prediction within the NAS [illegible] system. The areas dealt with include:

- core storage estimate
- processing time estimates
- method of scheduling
- table lock requirements

9.1 Core Storage Estimate

The storage estimate for Conflict Prediction is divided into two parts:

- data areas
- program areas

Each of these sections has been broken down into smaller subsections to show the areas included in the estimate. Each subsection was estimated from the most accurate source available for that section including coding some sections in detail. All estimates are based on programming Conflict Prediction in assembly language.

The storage estimates for the data areas, with the exception of the Temporary storage, (See Table 9.1), are based on the design of the tables involved. The Temporary storage estimate is based on the actual storage used in the Demonstration Version of Conflict Prediction in the 1b system. The tables that would affect the estimates due to a change in the number of aircraft

Time in seconds to process

per aircraft (1500 pairs)

	25%	50%	75%
[illegible]	3.9	3.1	2.0
[illegible]	4.6	3.5	2.4
[illegible]	5.2	3.9	2.6
[illegible]	5.[illegible]	4.4	2.8

Table 9.2

Timing Estimates

...fore, it is reasonable to assume that all aircraft could be processed every minute, as this would require less than 6% of ... The processing could be spread over the one minute interval or accomplished all at once.

..2.2 Aircraft Pair Reduction

This section contains a description of an alternate approach to processing rather than processing all aircraft at one time. This alternate method, with further study preferably in a working system or with actual system data, could prove valuable in reducing the required processing time.

The objective, of course, is to require as little processing time as possible. The parameter to control to decrease this time is the number of aircraft pairs that must be processed.

The question arises: What pair count would result if:

1. all aircraft were not processed on every pass of CP,
2. each aircraft were scheduled to be processed every n^{th} program execution,

A Monte Carlo approach was used to try to answer this question. A grid was drawn using the Y axis to represent the vertical aircraft altitude level distribution, the X axis to represent the n CP passes required to process the entire group. The aircraft in each altitude level where then randomly dis-

tributed through the n segments of the X axis, the number of pairs at each XY intersection calculated and the total pair count (by X axis time segment) totaled.

Three separate loadings were tried for 275 aircraft, and one for 450 aircraft. These loadings were segmented as follows:

n=15 - This is effectively the load if CP were scheduled every 20 seconds (1/3 min) and the plan was to process all aircraft every 5 minutes.

n=10 - This is the load if CP were scheduled every 30 seconds (1/2 min) and the plan was to process all aircraft every 5 minutes.

n=30 - This is the load if CP were scheduled every 20 seconds (1/3 min) and the plan was to process all aircraft every 10 minutes.

Note: If this approach were to be implemented, the use of a "hot item" indicator to pre-empt the normal scheduling cycle should probably be used.

Conclusions and Observations

1. By using the segmented approach the pair count was substantially reduced. When all aircraft were processed on every pass of CP, the pair counts were as follows:

Aircraft	Pairs Without Segments
275	1500
450	4200

However, when the aircraft were randomly distributed through the n segments of the X axis, the pair count per segment decreased by a large percentage. The following table shows the pair count reduction which resulted from the segmented approach.

Aircraft	Segments	Pairs Per Segment	Pair Count Reduction (%)
275	10	270	82%
275	15	195	87%
275	30	100	93%
450	10	800	81%

Hence, an n=10 value resulted in about 18% of the original load, an n=15 value resulted in about 13% of the original load, an n=30 value resulted in about 7% of the original load.

2. The processing of a particular aircraft pair will frequently occur twice during the time period $n_1, n_2, \ldots, n_{10}$. For example, if aircraft A is conflict checked with all other aircraft in the altitude level during

time segment n_1, and aircraft B checked with all other aircraft in the altitude level during time segment n_2, then the aircraft pair A-B will have been examined twice during the time interval n_1-n_{10}. If both are scheduled for the same segment, they will only be tested once. Hence, each pair will be processed at least once in the n_1-n_{10} timespan. The following table shows the load increase due to the segment approach.

Aircraft	Pairs Without Segments	Segments	Segmented Pairs Total	Pairs Per Segment (Average)	Total Pair Increase Factor
274	1500	10	2711	271	1.80
274	1500	15	2893	193	1.93
274	1500	30	2956	99	1.97
450	4200	10	7986	800	1.90

3. The calculations presented here assume that the aircraft in each altitude level are initially randomly scattered over n time segments (where n represents, say 5-10 minutes). After initial scattering, the processing pattern setup is consistently repeated over and over again.

In actual implementation, this would not be the case. Consider, for example, a flight which becomes active and is added to the processing scheme. It would be conflict checked immediately, then rescheduled for

checking n time segments later. If that flight has an altitude change, however, the flight should be re-conflict checked immediately and rescheduled for checking n time segments later. Hence, dynamic modification to the aircraft's data profile should pre-empt, or over-ride, normal periodic scheduling.

Let us try to calibrate the effect of dynamic re-scheduling on the processing. The following changes to the aircraft's data base should cause overrides to normal periodic scheduling:

a. New active IFR flight. Assume 2 new flights per 100 aircraft per minute.

b. Altitude modification. Assume 7 altitude modification per 100 aircraft per minute.

c. Speed modification. Assume 2 speed modifications per 100 aircraft per minute.

d. Route modification. Assume 2 route modifications per 100 aircraft per minute.

e. Deletion (or termination) of active flights. This action will not initiate immediate conflict prediction checking; hence, no processing load is incurred.

f. Modification of route fix CTA times. Assume 1 modification of fix CTA times per 100 aircraft per minute. (Not due to speed modification (see c above)).

g. Flight tracking status change (free÷flat÷hold÷delay÷ [illegible]). Assume 2.2 modifications to tracking status per 100 aircraft per minute.

Summing the above items which would impact conflict prediction scheduling, a total of 11.7 data base modifications per 100 aircraft per minute is estimated for the system. This may be extrapolated to 32.2 modifications per 275 aircraft per minute. Extrapolating this data again, we can calculate 275 modifications per 275 aircraft per 8.5 minutes.

If you assume that the 275 modifications are distributed uniformly over the 275 flights, then the flights would be completely rescheduled due to dynamic inputs every 8.5 minutes. In actual situations, however, this would not be the case. Some flights may not have any modification that would cause automatic rescheduling. However, the calculations may be used to reach this conclusion: When an aircraft is conflict checked, it should be scheduled to be re-checked at a time which is at least 8.5 minutes in the future.

h. The previous paragraph estimated 32.3 changes (which would pre-empt normal periodic scheduling) per 275 aircraft per minute. The following table shows the effect of these pre-empts on the number of aircraft pairs which require processing.

Aircraft	Segments	[illegible]	Time Per Segments	Pre-empts Per Segments	Aircraft Pairs Per Segment With Pre-empt	Without Pre-empt
274	10	5 min	1/2 min	16	369	271
274	15	5 min	1/3 min	11	248	193
274	30	1[illegible] min	1/3 min	11	170	99

It should be pointed out that the above assumes instaneous altitude changes. It does not take into account that, during an altitude change, an aircraft may be recorded in several different altitude levels.

9.3 Method of Scheduling

The most suitable method of scheduling Conflict Prediction in the [illegible] system seems to be for RATK to DEMAND the program every [illegible] radar scan. This would result in processing every n x 10 [illegible].

9.4 Table Data Requirements

During processing, Conflict Prediction will utilize data in the following Compool tables:

Flight Plan Index Table (FPIN)

Aircraft State Record Table (AKRR)

Tracking Data Table (TKDT)

Plan View Display Table (PVDT)

Sector Index Table (SCID)

Monitor Miscellaneous Table (MISC)

The only tables requiring locks are FPIN and TKDT. However, since FPIN and TKDT will be used as read-only tables by Conflict Prediction locking may not be necessary. To determine the effect of the presence/absence of table locks on the accuracy of the Conflict Prediction process, on-line testing or simulation modeling must be performed.

10.0 Recommendations

Although the discussion of Conflict Prediction in this paper is centered around NAS Model 1 environment, the NAS Advanced Programming Department feels that the prediction scheme is applicable to current and future Air Traffic Control systems. In view of this the Department suggests a possible phasing plan for future work with Conflict Prediction.

Initially Conflict Prediction could be integrated into the JAX it system for testing purposes. In this system all the methods of prediction could be tested:

- the method of handling aircraft not under radar coverage;
- the method of processing those aircraft that do have radar coverage;
- the method of determining conflicts between aircraft in altitude changes.

Also, various scheduling algorithms could be tested to determine which is the most efficient.

At such time during this testing that it is deemed apropos a method of integration into the NFDP system could be planned. It is felt that there are worthwhile possibilities for CP within NFDP. Using non-radar separation standards the flight plans could be conflict checked initially and rechecked with each flight plan amendment. This could be accomplished on a probe or automatic basis, or a combination of the two. A phased implementation from probe to automatic or probe to a probe-automatic combination would be another possibility.

Integration into the final system (i.e., the system with radar processing) should be the ultimate goal for Conflict Prediction. Testing in the Model 1b JAX system could prove invaluable to implementation of Conflict Predication in the final system. A phased implementation here could have even more flexibility than in NFDP. One possible additional use for Conflict Prediction worth mentioning would be as a probe by the controller to determine if a proposed altitude change is conflict free.

At some point in time it is felt that serious consideration should be given to attaching Conflict Resolution to the plans for the future. Algorithms currently exist for most cases of resolving conflicts. An excerpt from the paper "Ground Based Collision Avoidance Function for the 1980 Air Traffic Control System" by Pessman and Kirchoff is contained in Appendix E.

This excerpt explains the existing resolution algorithms. Since Conflict Resolution depends on Conflict Prediction to recognize the situation that needs resolving and to determine that the solution is conflict free, a phased integration approach could be adopted. Both the NFDP and radar systems could accommodate Conflict Resolution on a request basis by the controlling personnel or automatically with the prediction of a conflict. The ultimate goal for Resolution in the near future is to be a tool for the controller and to suggest to him possible courses of action to alleviate conflict situations.

These suggestions are by no means exhaustive. There are many other possible courses of action, however this Department feels that at this time the described approach would be a sound and appropriate path for the future.

Appendix A

SAT FILTERING EFFECTIVENESS

One of the problems of Conflict Prediction is the large number of aircraft pairs which must be processed by the computer. Consider, for example, the task of conflict checking every IFR aircraft in the system against every other IFR aircraft in the system. The result of this requirement is a machine load which grows exponentially as the number of IFR aircraft increases. In a system which contains N number of IFR aircraft, the number of unique IFR pairs which must be conflict checked is equal to $\binom{N}{2}$, or (N) (N-1)/2. The magnitude of the computer load can be shown in the following table.

Aircraft	50	100	150	200	250	300
Aircraft Pairs	1,225	4,950	11,175	19,900	31,125	44,850

The Segregated Altitude Table (SAT) is a mechanism which will substantially reduce the computer's processing load by reducing the number of aircraft pairs which must be conflict checked. In the enroute environment IFR aircraft, once they reach their selectod altitude, will tend to cruise in level flight. Altitude maneuvers may be performed enroute, but the

000 99

essential point is that while enroute the large majority of aircraft time will be spent in level flight. Therefore, if the aircraft data in the computer can be maintained in segregated groups which insure vertical separation, it will only be necessary to horizontally conflict check aircraft pairs which occur at the same altitude strata. The SAT is designed to accomplish this function.

Page A-3 of this appendix is a table of Estimated Altitude Distribution of Enroute IFR Aircraft. Using these percentages it is possible to:

(1) project a vertical distribution of airborne IFR aircraft,

(2) calculate the number of aircraft pairs at each altitude strata, and

(3) calculate the total number of aircraft pairs Conflict Prediction must process by summing the pairs in all altitude strata.

Page A-4 shows the result of this calculation. The aircraft distribution was calculated in increments of 25 aircraft, with some variation due to rounding. The magnitude of the computer load and the SAT reduction is summarized in the following table.

000100

TABLE A-1

Estimated Altitude Distributions of Enroute IFR Aircraft, Peak Minute, CY 1959, FY 1966 and FY 1975*

Assigned Altitude in feet	Airborne Aircraft 1959	Airborne Aircraft 1966	Airborne Aircraft 1975	Percentage Distributions 1959	Percentage Distributions 1966	Percentage Distributions 1975	Cumulative Percentages 1959	Cumulative Percentages 1966	Cumulative Percentages 1975
up to 1,999	5	44	190	0.2	1.8	3.2	0.2	1.8	3.2
2,000 - 3,999	195	85	241	7.2	3.4	4.0	7.4	5.2	7.2
4,000 - 5,999	527	352	776	19.5	14.5	12.9	26.9	19.7	20.1
6,000 - 7,999	614	453	851	22.7	18.1	14.2	49.6	37.8	34.3
8,000 - 9,999	426	303	521	15.7	12.1	8.7	65.3	49.9	43.0
10,000 - 11,999	264	154	286	9.8	6.1	4.8	75.1	56.0	47.8
12,000 - 13,999	168	102	167	6.2	4.0	2.8	81.3	60.0	50.6
14,000 - 15,999	114	80	157	4.2	3.2	2.6	85.5	63.2	53.2
16,000 - 17,999	90	60	136	3.3	2.4	2.3	88.8	65.6	55.5
18,000 - 19,999	79	82	217	2.9	3.2	3.6	91.7	68.8	59.1
20,000 - 21,999	52	85	247	1.9	3.4	4.1	93.6	72.2	63.2
22,000 - 23,999	27	72	222	1.0	2.9	3.7	94.6	75.1	66.0
24,000 - 25,999	22	118	373	.8	4.7	6.2	95.4	79.8	73.1
26,000 - 27,999	33	65	213	1.2	2.6	3.5	96.6	82.4	76.6
28,000 - 29,999	36	118	374	1.3	4.7	6.2	97.9	[illegible]7.1	82.8
[illegible]	23	98	316	.8	3.9	5.2	98.7	91.0	88.[illegible]
[illegible]	12	72	232	.4	2.9	3.8	99.1	[illegible]	91.4
[illegible]	[illegible]	[illegible]	[illegible]	.9	6.1	[illegible]	100.[illegible]	[illegible]	[illegible]
Total	[illegible]	[illegible]	[illegible]	100.0	100.0	[illegible]			

* Sums of individual Air Route Traffic Control Center peak minute counts, about [illegible] percent greater than the simultaneous nationwide peak. [illegible] percent of military flights in [illegible].

000101

AIRCRAFT	49	102	151	200	248	301
PAIRS (WITHOUT SAT)	1,176	5,151	11,325	19,900	30,628	45,150
PAIRS (WITH SAT)	25	173	427	766	1,232	1,811
REDUCTION OF PAIRS	1,151 (98%)	4,978 (96%)	10,898 (96%)	19,134 (96%)	29,396 (96%)	43,339 (96%)

These calculations assume that all aircraft are in level flight and are therefore reflected in only one strata of altitude in the SAT.

000102

Appendix B

SAT DESIGN AND MAINTENANCE

Design

The Segregated Altitude Table (SAT) will be a table of flight plan pointers which are segregated by altitude level. In implementation, the SAT will be divided into two parts — the SAT and its index:

1. The SAT will be a table of flight plan pointers. The table will consist of 750 one word entries organized into chains by altitude level.

2. The SAT INDEX table will be ordered by altitude level. The index table will contain two items of information: a pointer to the first SAT entry in the flight plan pointer chain, and the count of the number of entries in the chain. The SAT INDEX will consist of 46 one-word entries:

Entries 0-29	Altitude levels 000-290, in increments of 1000 feet
Entries 30-44	Altitude levels 310-590, in increments of 2000 feet
Entry 45	Altitude levels of 610 and above

A diagram of the SAT and SAT INDEX tables is shown on page B-4 of this appendix.

000103

Initialization

For the STARTUP procedure, the SAT and SAT INDEX table must be initialized to zero.

Maintenance

The Conflict Prediction pre-processing task will provide maintenance of the SAT and the SAT INDEX tables. The addition of a new SAT entry in an altitude level will require

1. locating an empty entry in the SAT,
2. moving the flight plan pointer to the new entry,
3. setting the new entry to chain to the first entry in the existing SAT chain for that altitude level,
4. changing the SAT INDEX to point to the new SAT entry as the first entry in the SAT chain, and
5. incrementing the count of chained SAT entries recorded in the SAT INDEX table.

The deletion of a SAT entry is basically the reverse of this process. The deletion process involves scanning the SAT chain searching for the entry to be deleted, then closing the chain, setting the deleted entry to zero and decrementing the count of chained SAT entries in the SAT INDEX table.

Usage

The basic function of the SAT is as an altitude filter to reduce processing of aircraft pairs. IFR separation standards between aircraft require a vertical separation of

1000' up to and including an altitude of 29,000', and

2000' above 29,000'

The SAT is designed with these standards in mind. For example, an aircraft flying at 6,000' and an aircraft flying at 7,000' will be recorded in different altitude levels in the SAT. They meet the IFR separation standards and are safely separated, which is inherent in being recorded in different SAT levels. They will have to be conflict checked with the other aircraft in their respective levels, but need not be conflict checked with each other.

An aircraft flying at 6,500', however, can potentially be in conflict with aircraft in both the 6,000' and the 7,000' altitude level. Therefore, aircraft not at cardinal altitudes must be recorded in multiple SAT entries (i.e., in both the 6,000' and the 7,000' level). This rule will be extended to odd cardinal altitudes for aircraft above 29,000'.

Similarly, Mode C equipped aircraft executing an altitude maneuver and aircraft assigned block altitudes will require multiple entries in the SAT.

Altitude	Level	Entry
0,000'	000	0
1,000'	010	1
2,000'	020	2
3,000'	030	3
4,000'	040	4
.	.	.
.	.	.
.	.	.
27,000'	270	27
28,000'	280	28
29,000'	290	29
31,000'	310	30
33,000'	330	31
35,000'	350	32
37,000'	370	33
.	.	.
.	.	.
.	.	.
57,000'	570	43
59,000'	590	44
61,000'	610-999	45

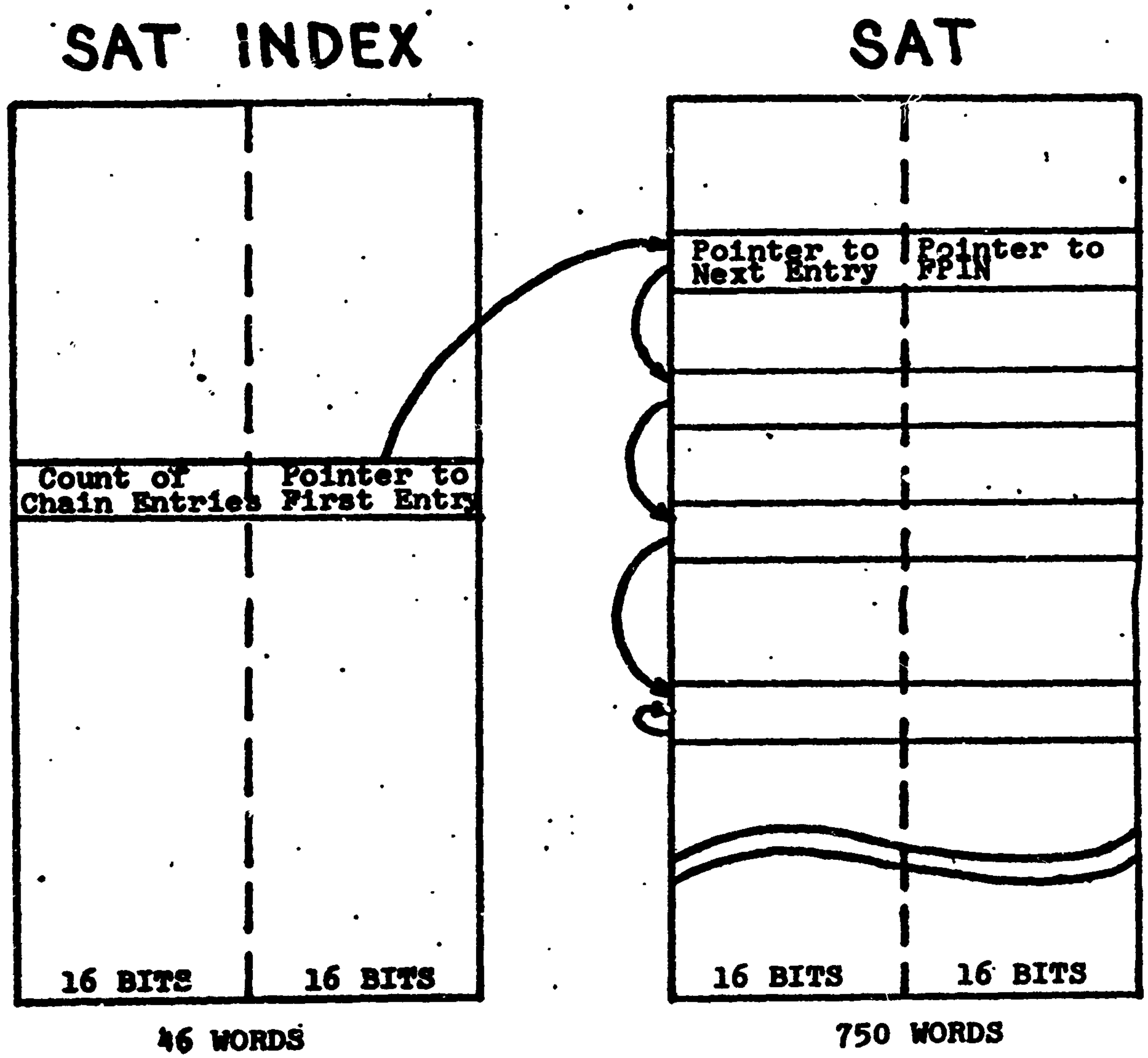


Figure B-1

000106

APPENDIX C

Flow Charts

This Appendix contains functional flows of the Conflict Prediction process for non-radar and radar covered IFR aircraft.

These flow charts are not meant to be a programming guideline, and the techniques illustrated in the charts may not be the most efficient for accomplishing the Conflict Prediction tasks. The flow charts are presented here only to clarify the logic for the processing of IFR aircraft.

The following is a list of acronyms used in the flow charts:

AC - Aircraft

CSI - Conflict Search Interval

CTA - Calculated Time Arrival

GRF - Gross Range Filter

NRS - Next Route Segment

OA - Overlap Area (Route width overlap area in shallow angle case)

PCA - Point of Closest Approach (Actually two points - the position of the parent at TCA and the position of the intruder at TCA)

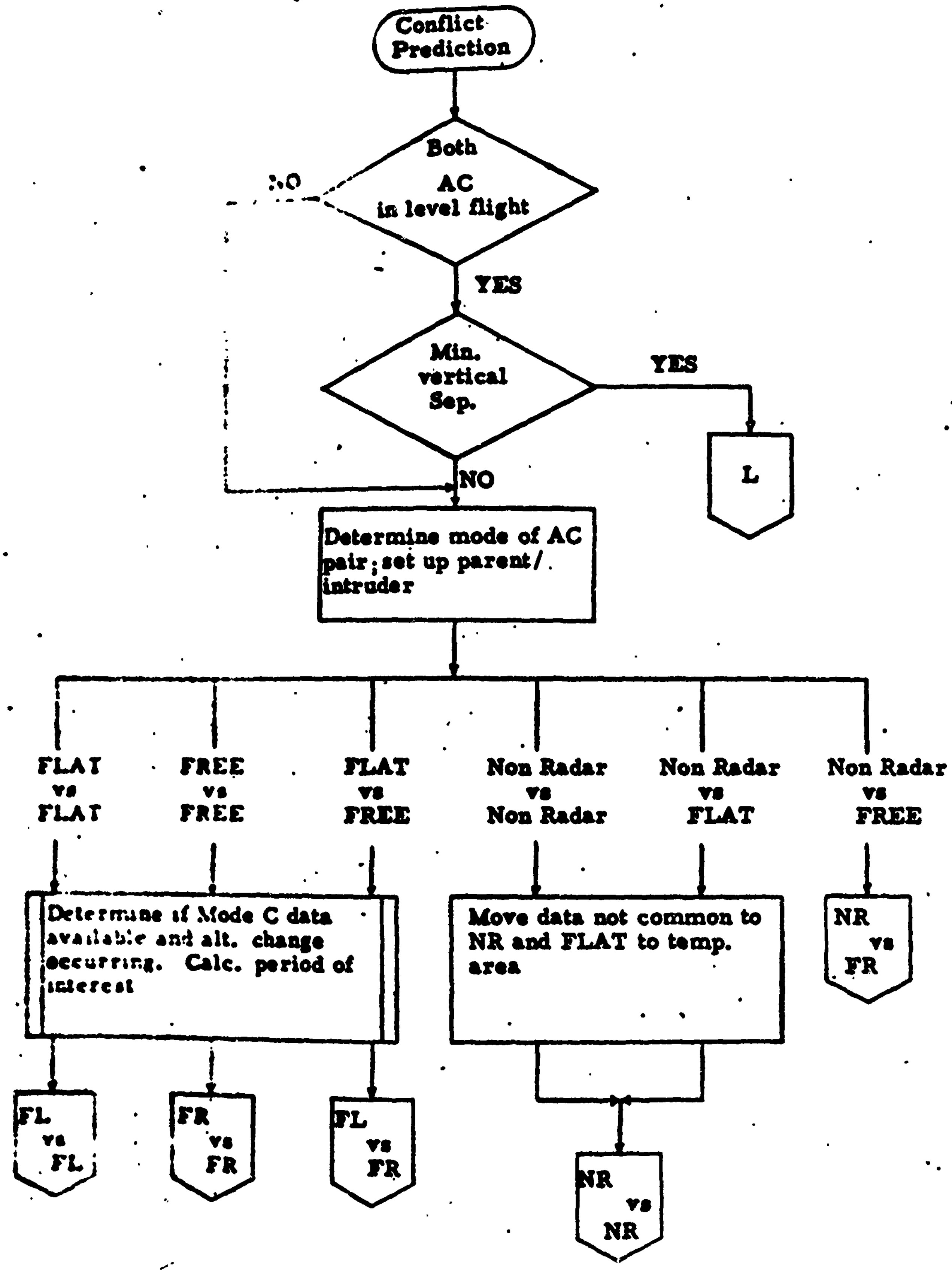
[illegible] - Radius of Closest Approach

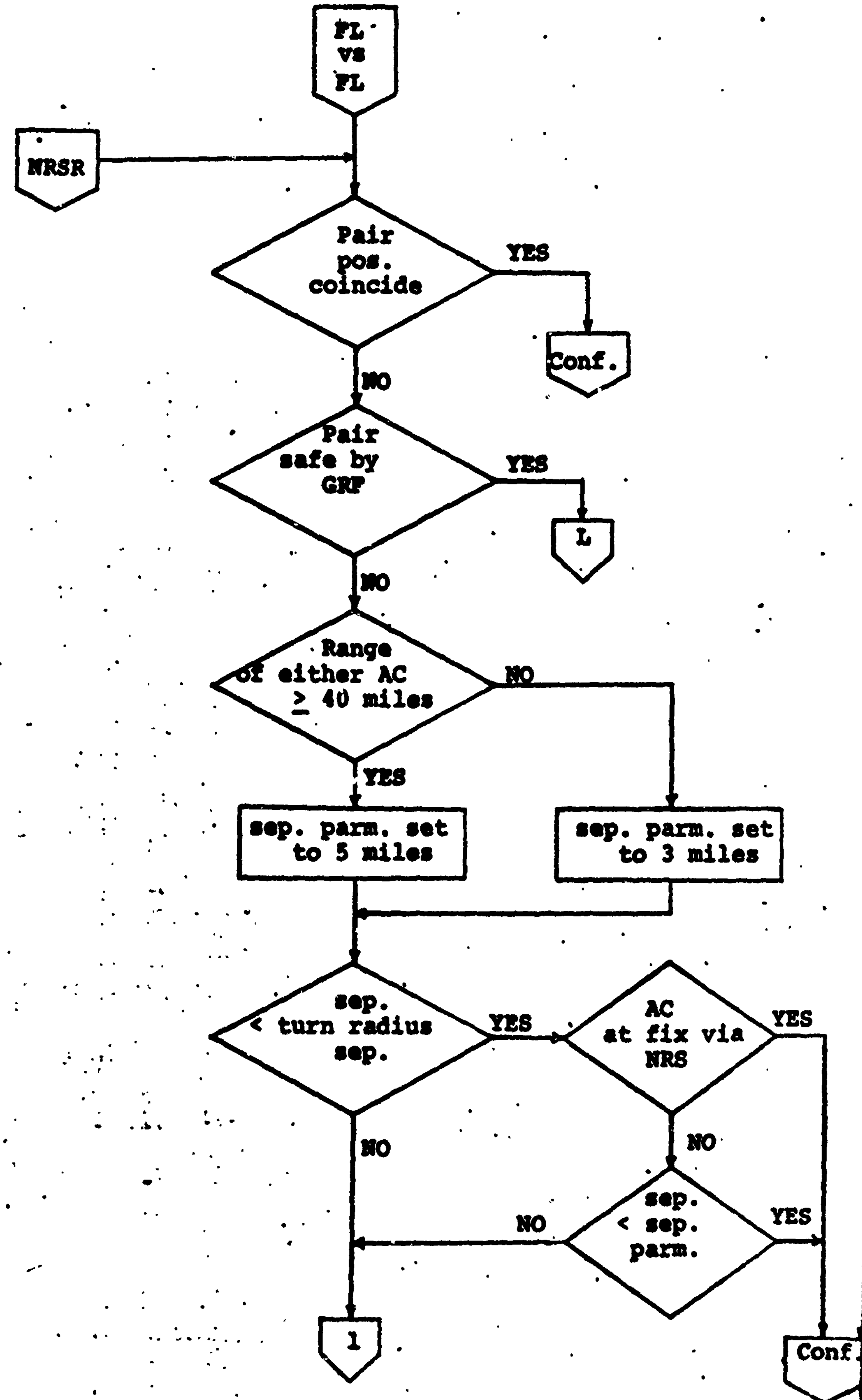
[illegible] - Relative Motion Filter

[illegible] - Time of Closest Approach

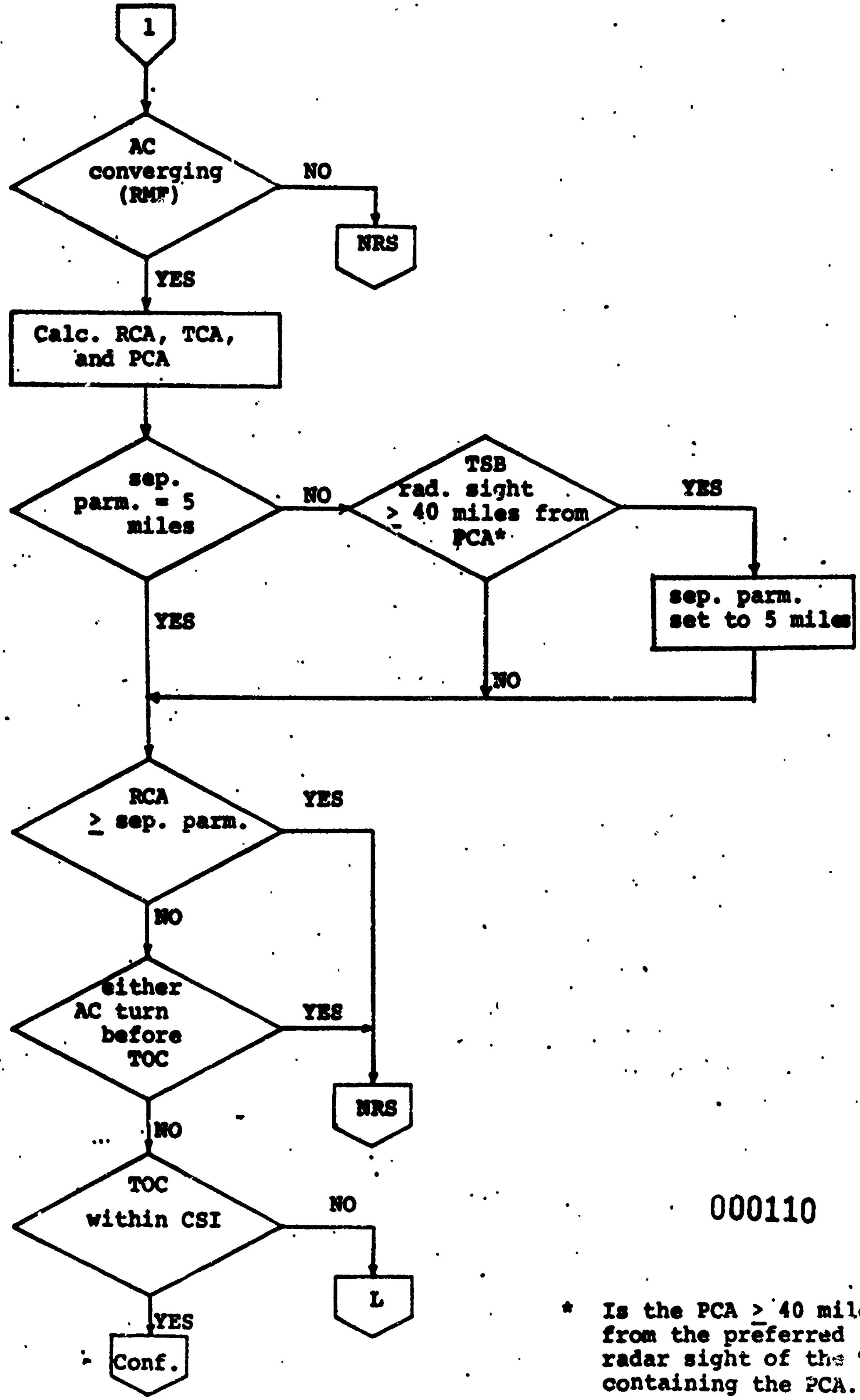
[illegible] - Time of Conflict

[illegible] - Track Sort Box


Conflict Prediction
Both AC in level flight
NO
YES
Min. vertical Sep.
YES
L
NO
Determine mode of AC pair; set up parent/intruder
FLAT vs FLAT
FREE vs FREE
FLAT vs FREE
Non Radar vs Non Radar
Non Radar vs FLAT
Non Radar vs FREE
Determine if Mode C data available and alt. change occurring. Calc. period of interest
Move data not common to NR and FLAT to temp. area
NR vs FR
FL vs FL
FR vs FR
FL vs FR
NR vs NR

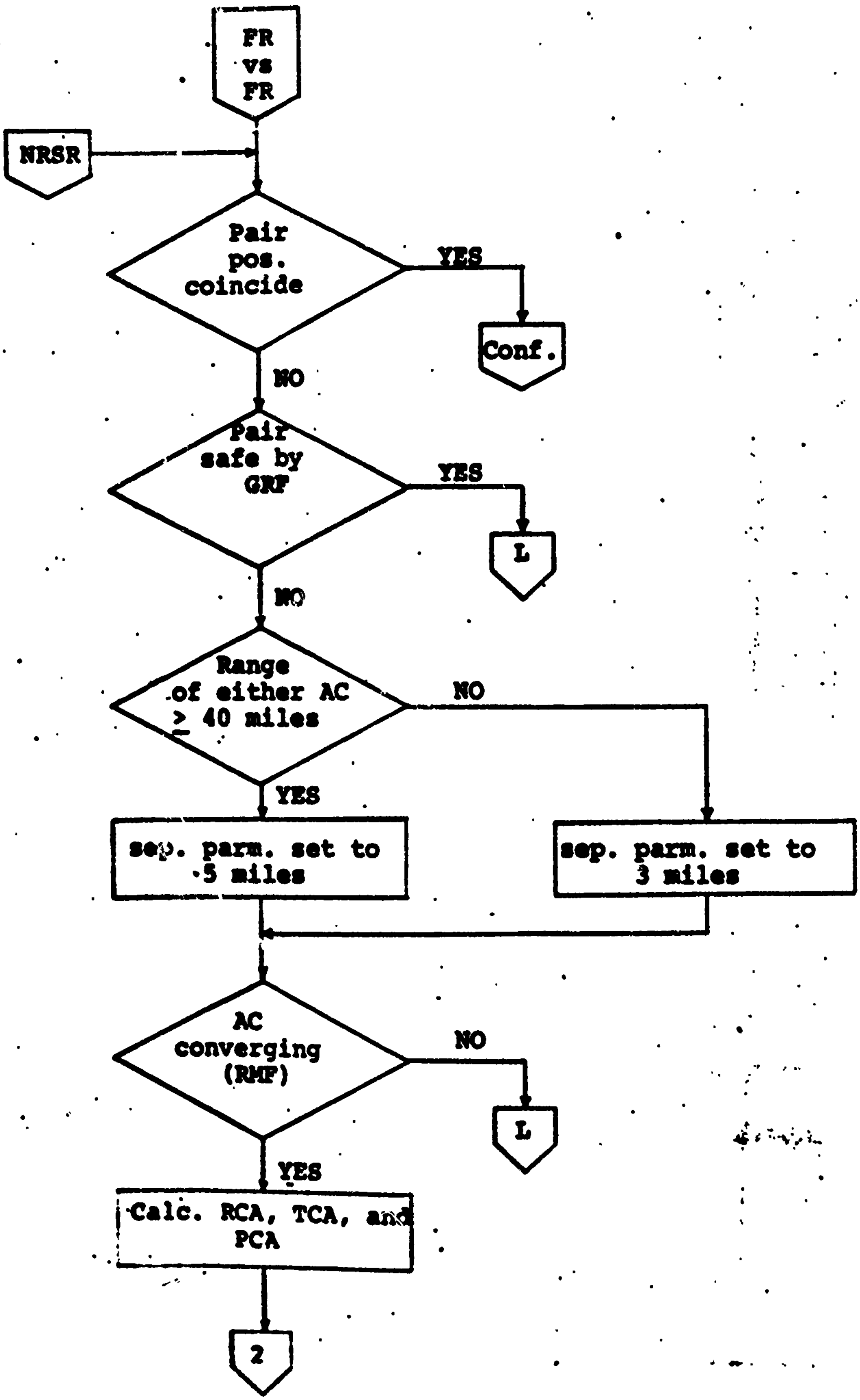

FL
VS
FL
NRSR
Pair
pos.
coincide
YES
Conf.
NO
Pair
safe by
GRF
YES
L
NO
Range
of either AC
≥ 40 miles
NO
YES
sep. parm. set
to 5 miles
sep. parm. set
to 3 miles
sep.
< turn radius
sep.
YES
AC
at fix via
NRS
YES
NO
NO
sep.
< sep.
parm.
NO
YES
1
Conf

000109



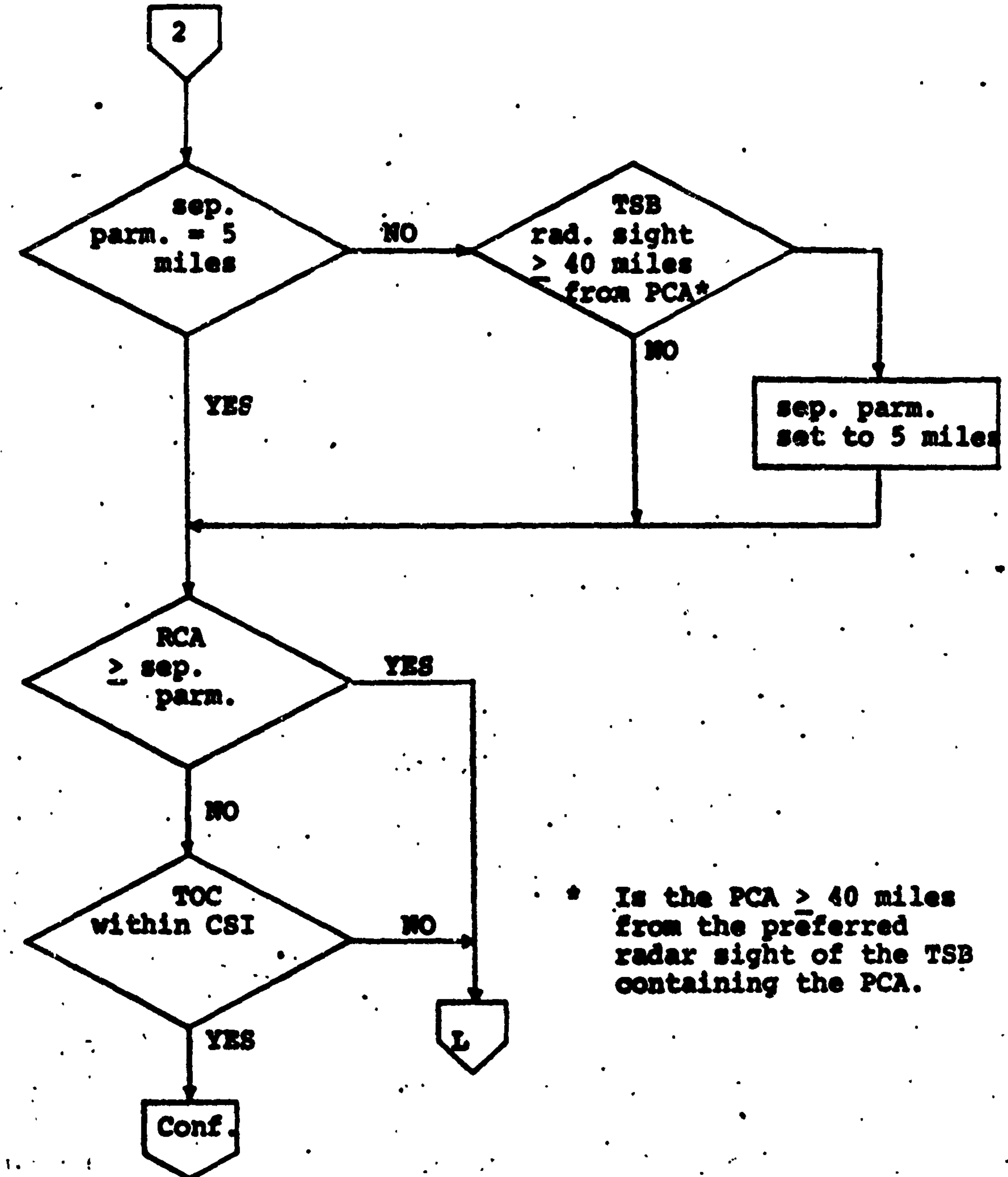
000110

* Is the PCA ≥ 40 miles from the preferred radar sight of the TSB containing the PCA.

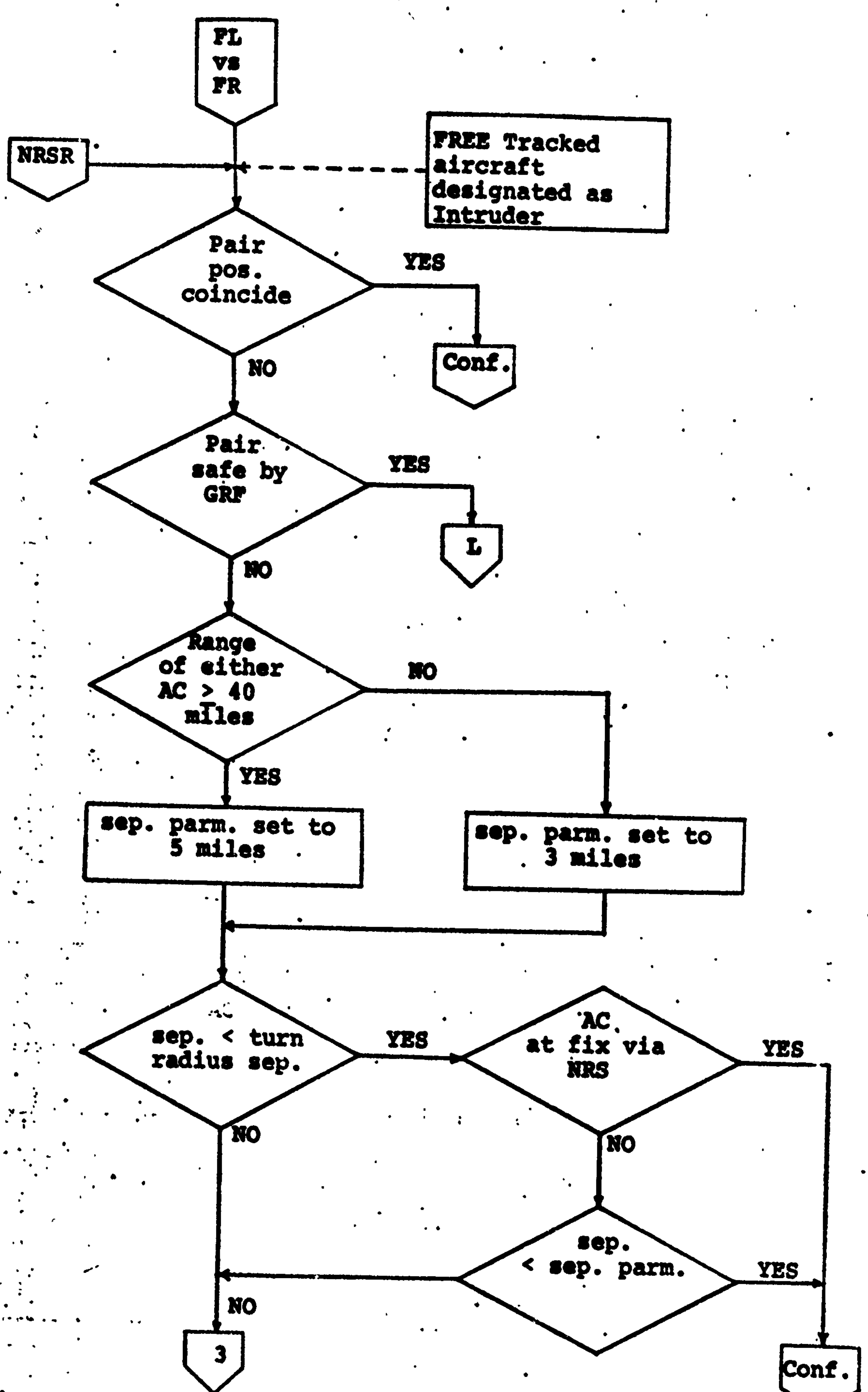


FR vs FR
NRSR
Pair pos. coincide
YES
Conf.
NO
Pair safe by GRF
YES
L
NO
Range of either AC ≥ 40 miles
NO
YES
sep. parm. set to 5 miles
sep. parm. set to 3 miles
AC converging (RMF)
NO
L
YES
Calc. RCA, TCA, and PCA
2

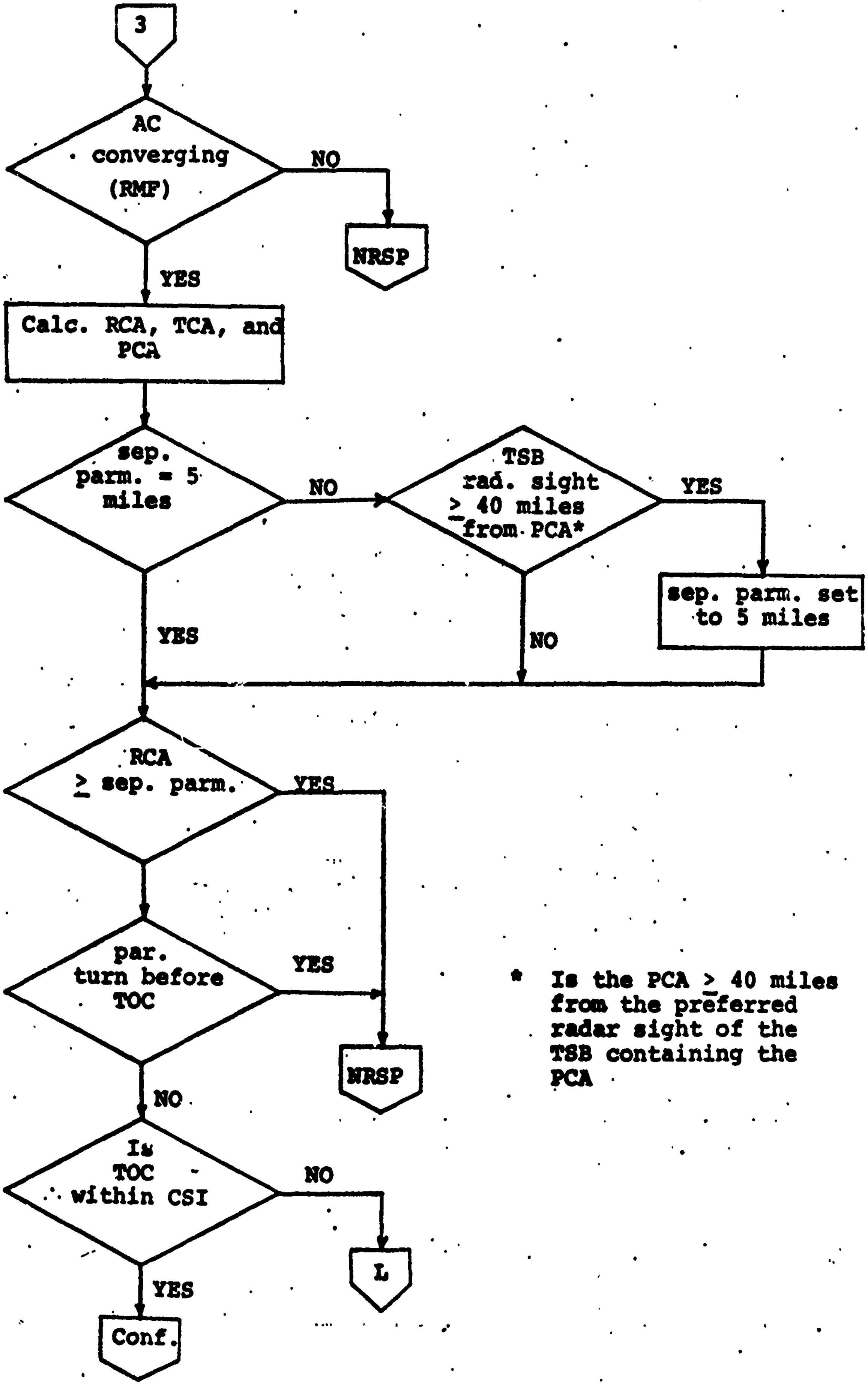
000111



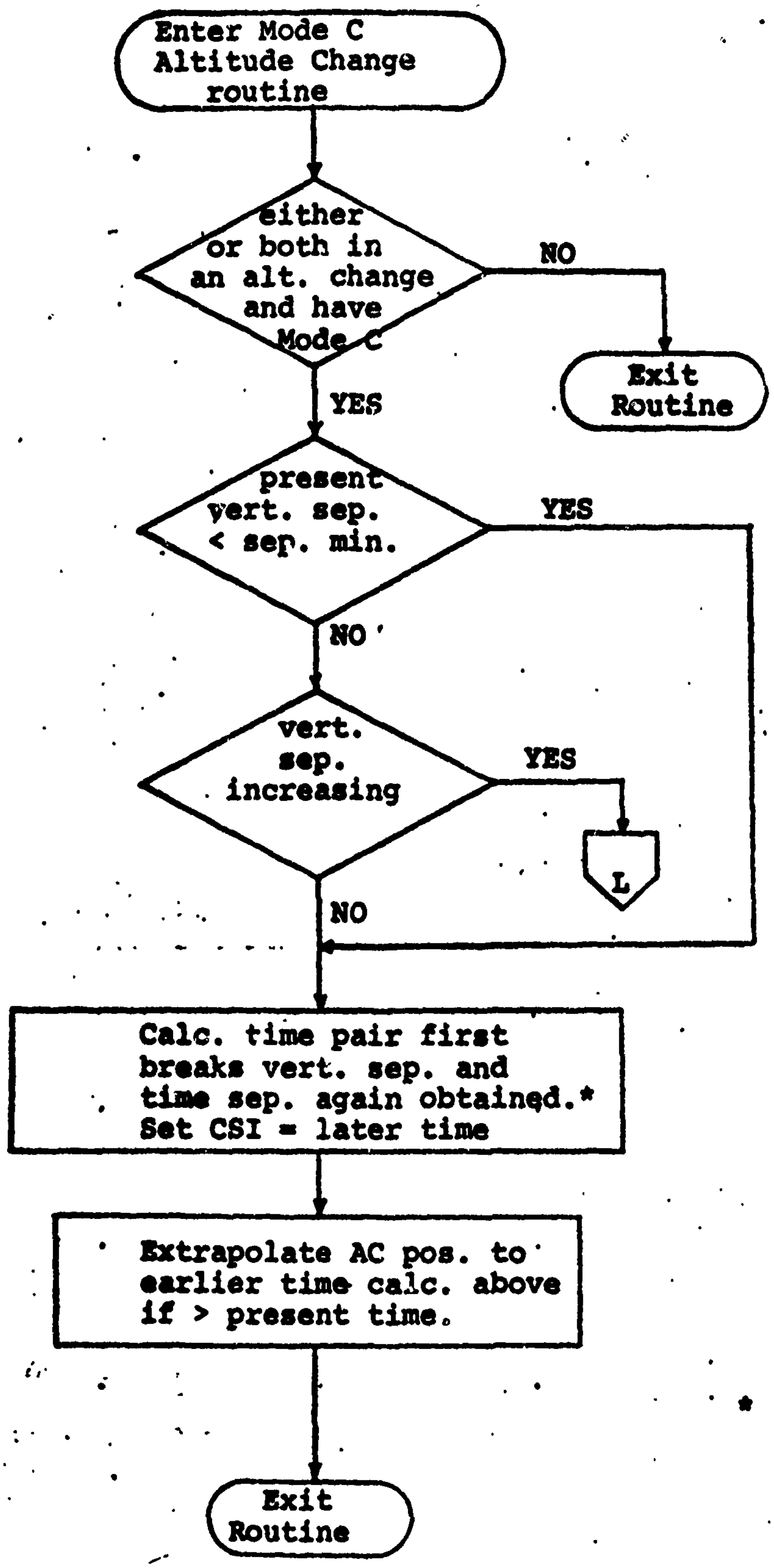
* Is the PCA ≥ 40 miles from the preferred radar sight of the TSB containing the PCA.


FL vs FR
NRSR
FREE Tracked aircraft designated as Intruder
Pair pos. coincide
YES
Conf.
NO
Pair safe by GRF
YES
L
NO
Range of either AC > 40 miles
NO
YES
sep. parm. set to 5 miles
sep. parm. set to 3 miles
sep. < turn radius sep.
YES
AC at fix via NRS
YES
NO
NO
sep. < sep. parm.
YES
NO
3
Conf.

000113

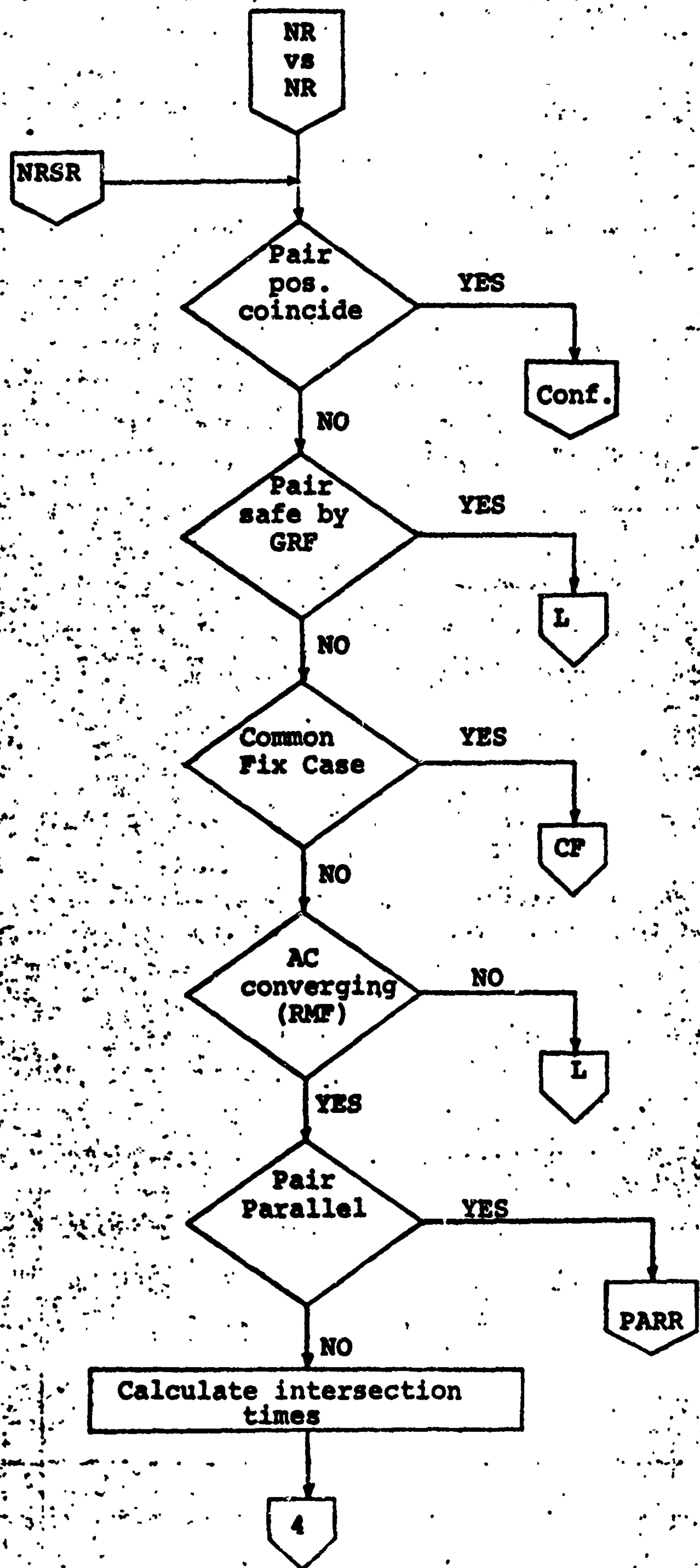


* Is the PCA ≥ 40 miles from the preferred radar sight of the TSB containing the PCA

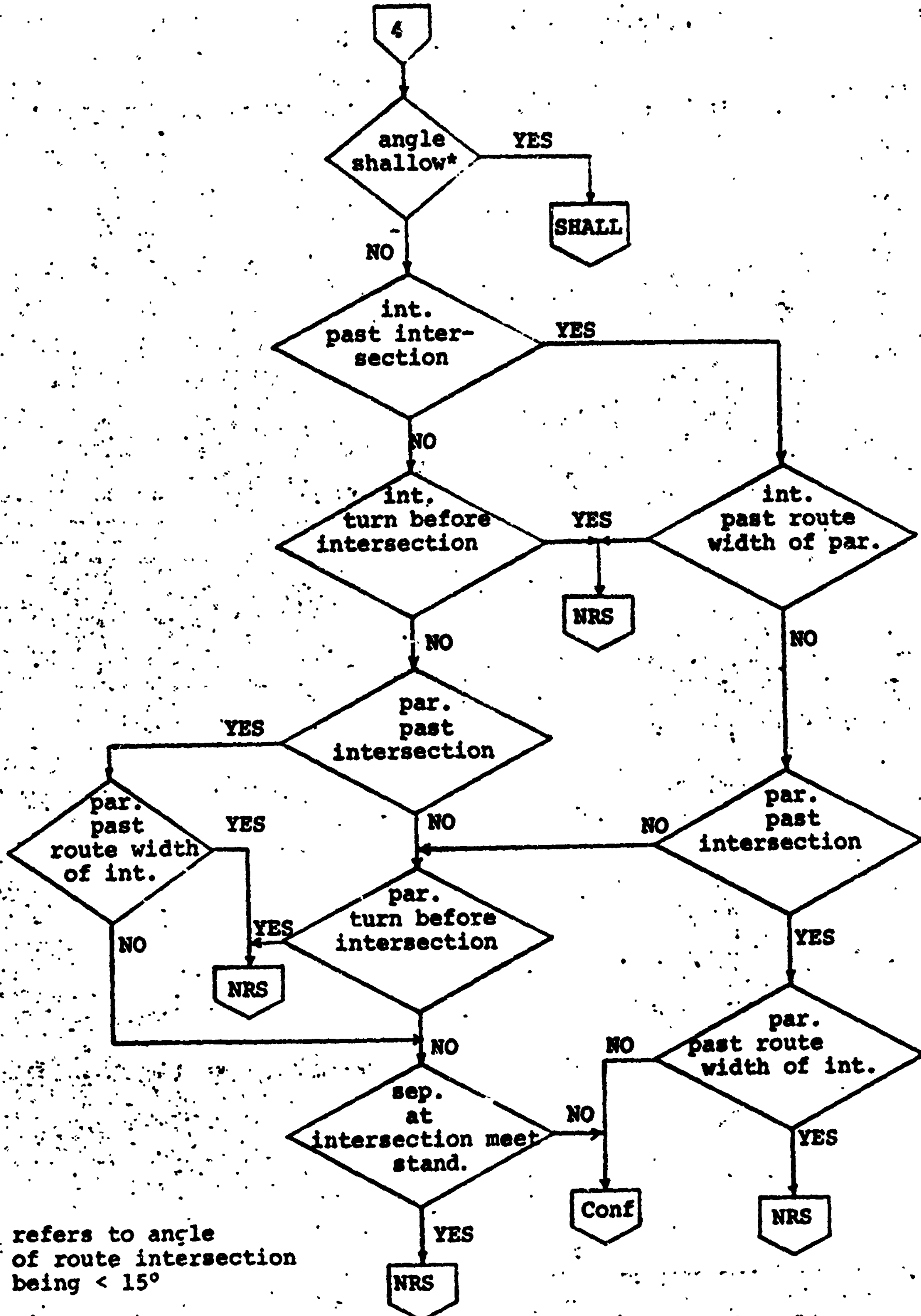


* This defines the period of interest (POI) for horizontal checking.

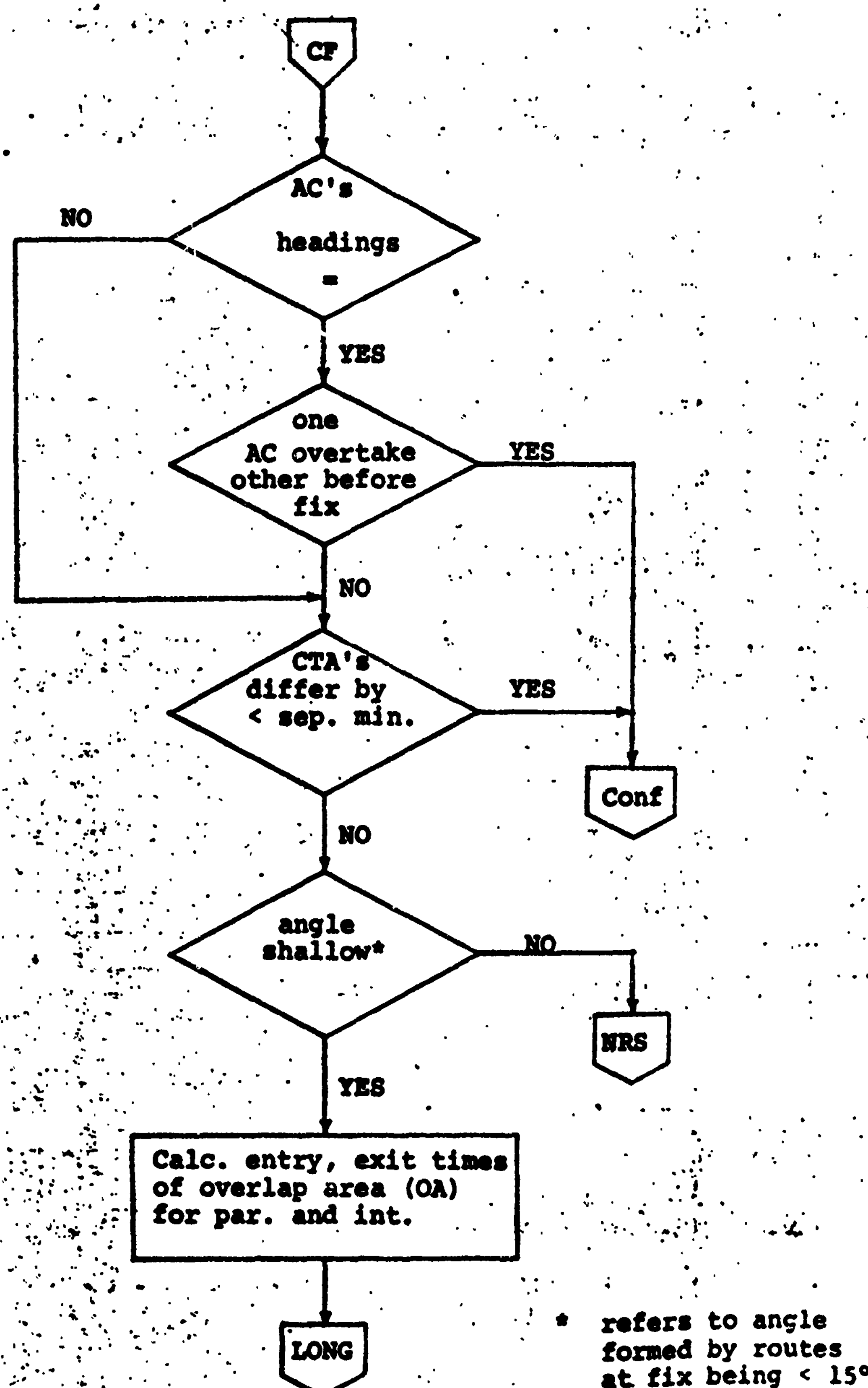
000115

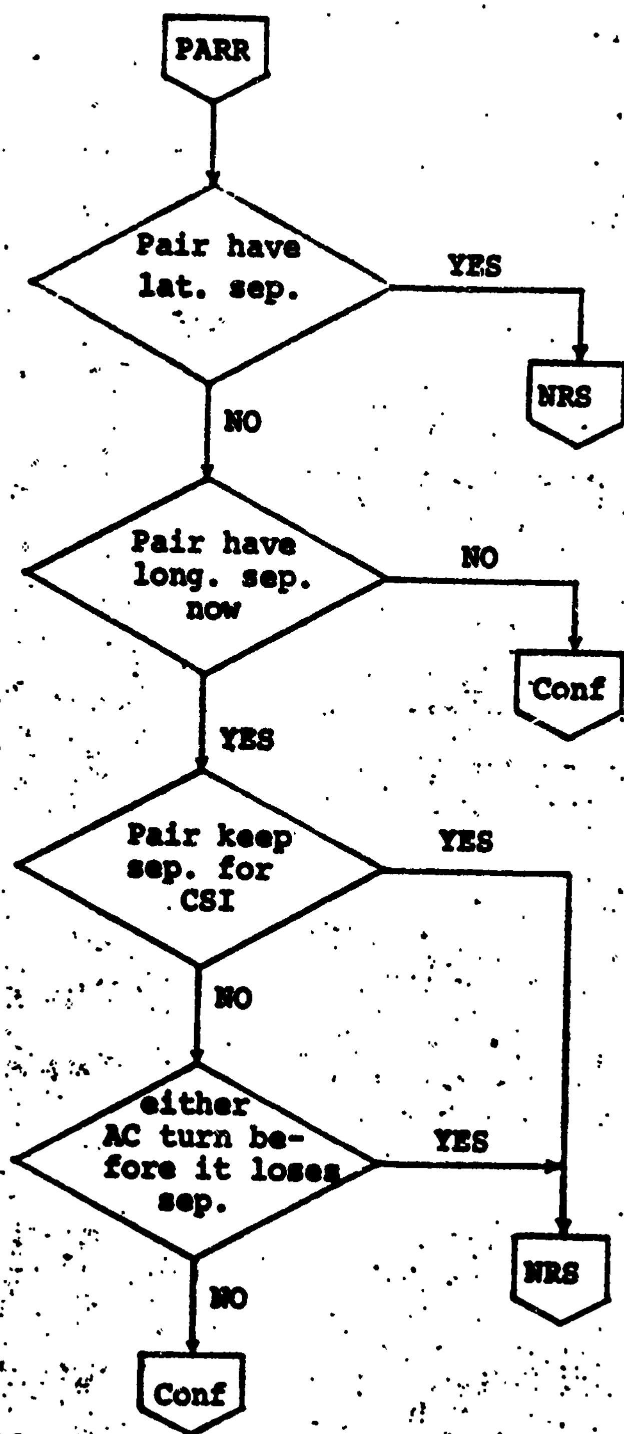

NR vs NR
NRSR
Pair pos. coincide
YES
Conf.
NO
Pair safe by GRF
YES
L
NO
Common Fix Case
YES
CF
NO
AC converging (RMF)
NO
L
YES
Pair Parallel
YES
PARR
NO
Calculate intersection times
4

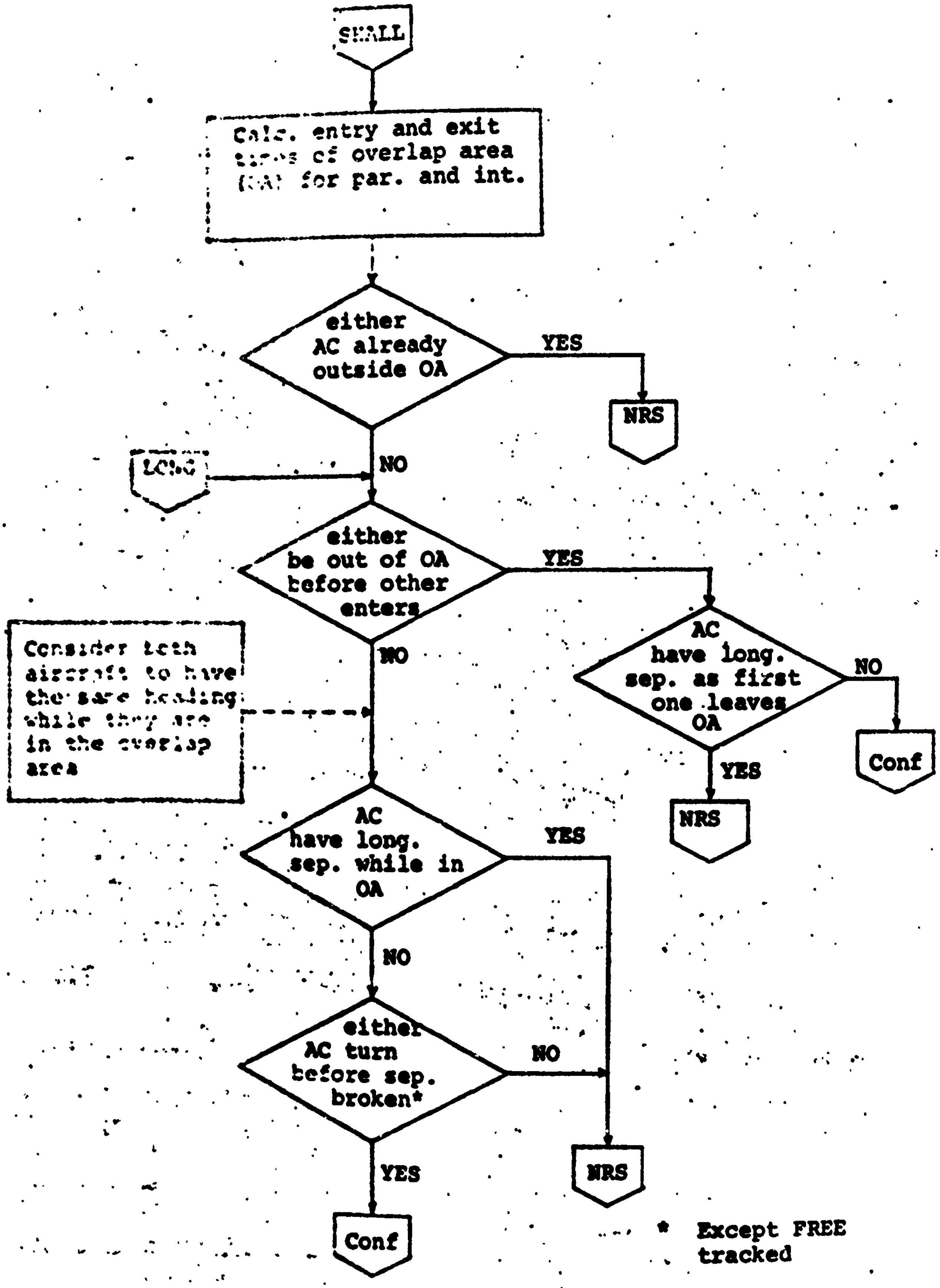
000116



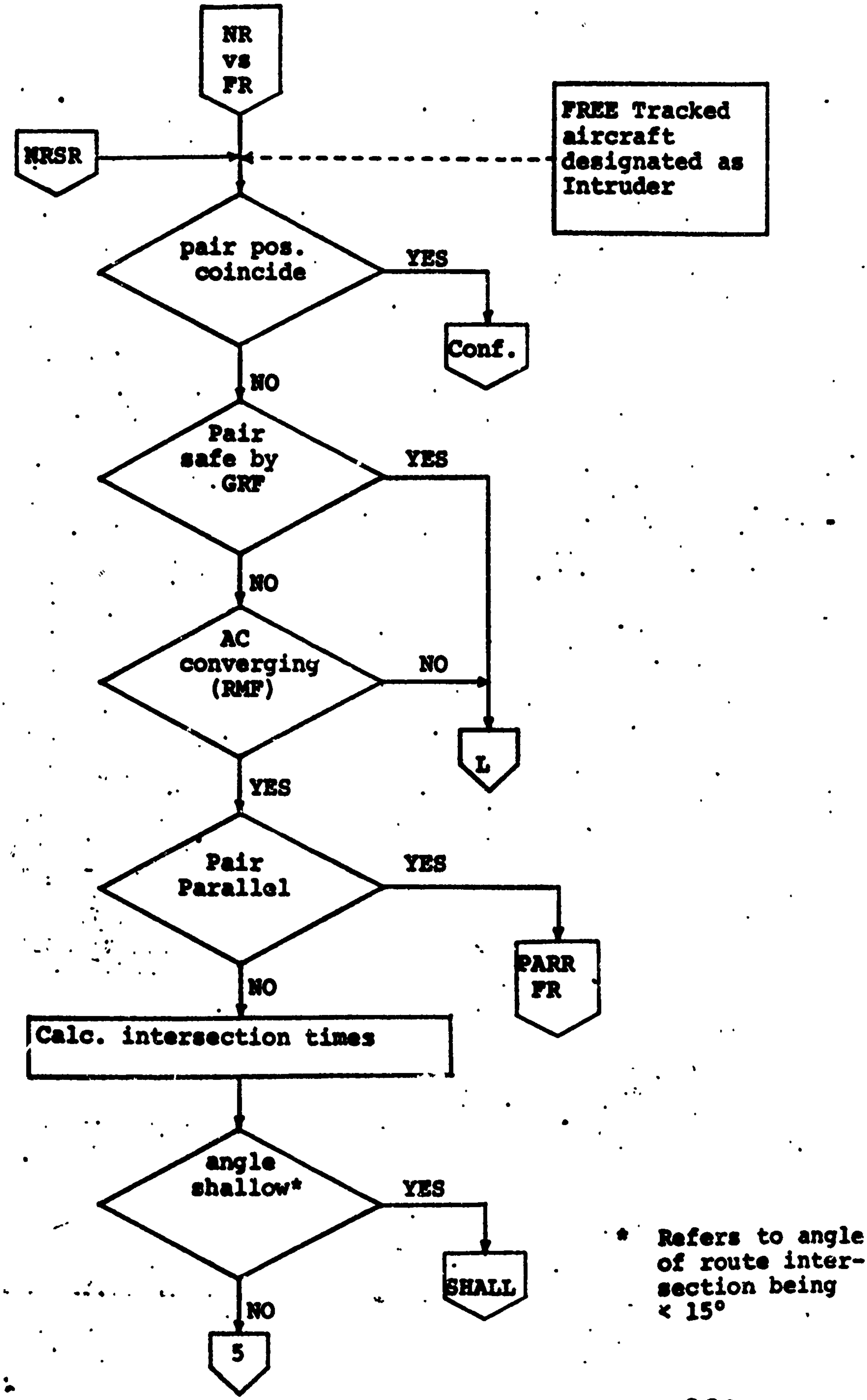
* refers to angle of route intersection being < 15°

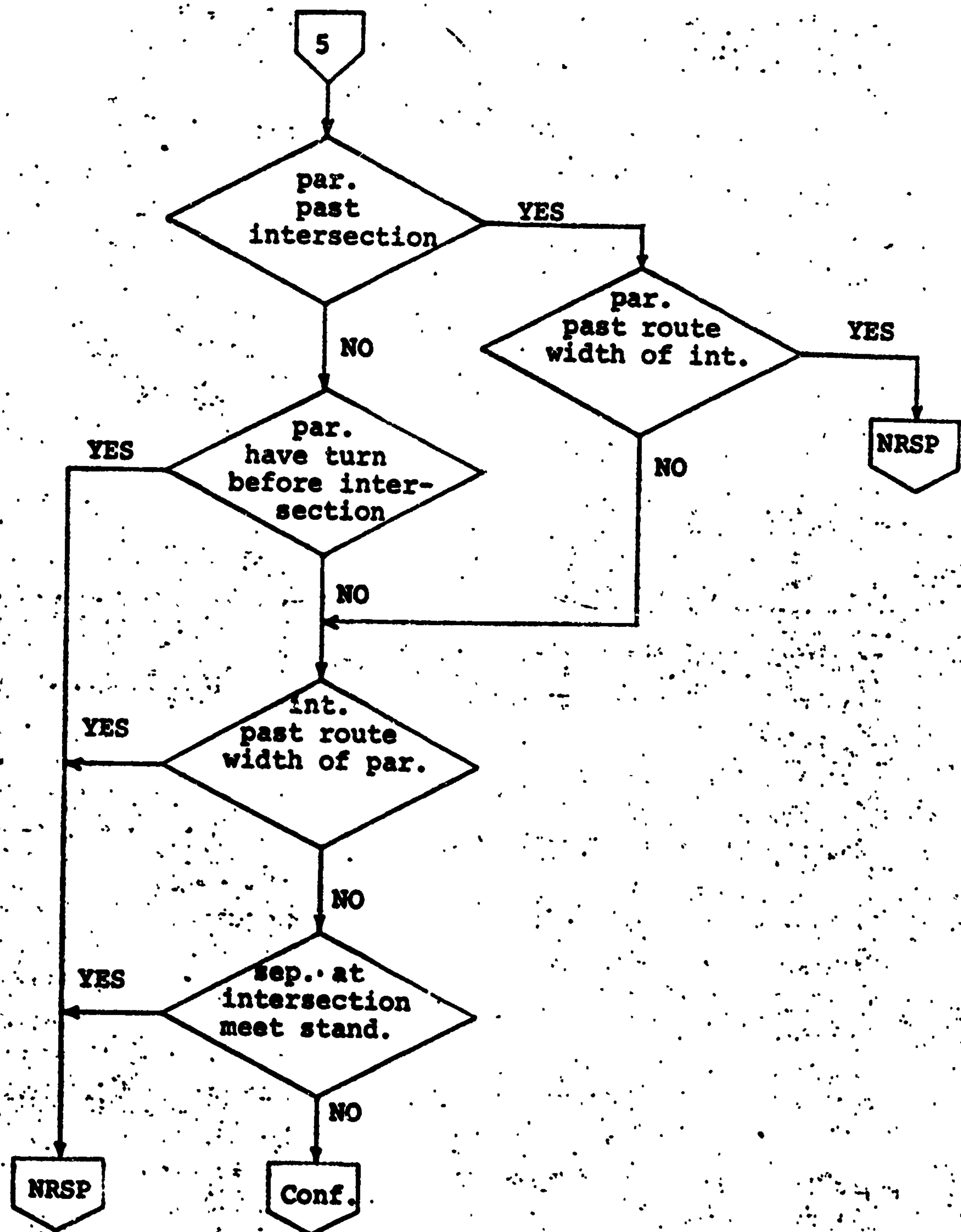

CF
AC's headings =
NO
YES
one AC overtake other before fix
YES
NO
CTA's differ by < sep. min.
YES
Conf
NO
angle shallow*
NO
NRS
YES
Calc. entry, exit times of overlap area (OA) for par. and int.
LONG
* refers to angle formed by routes at fix being < 15°


PARR
Pair have lat. sep.
YES
NRS
NO
Pair have long. sep. now
NO
Conf
YES
Pair keep sep. for CSI
YES
NO
either AC turn be- fore it loses sep.
YES
NRS
NO
Conf

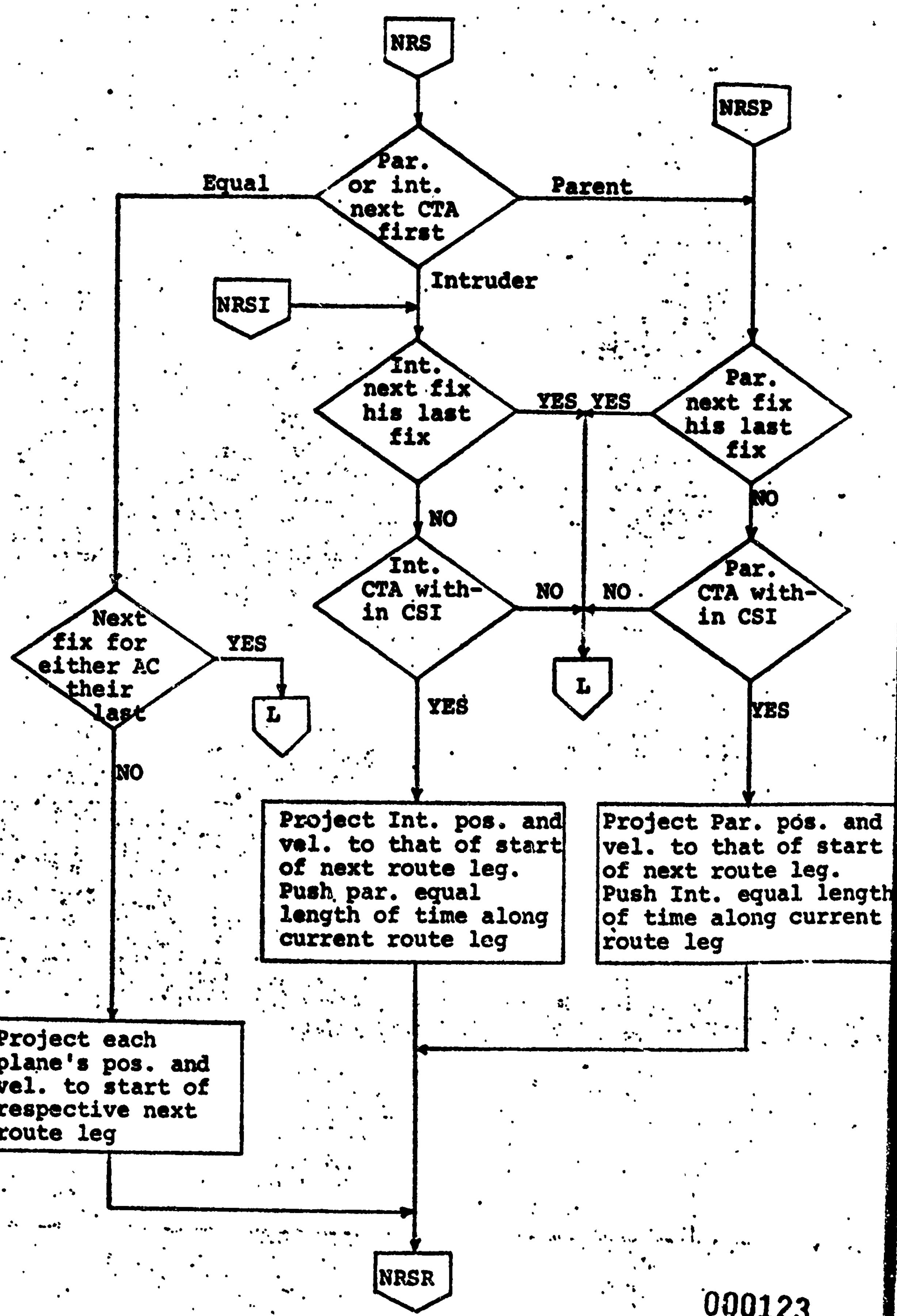


* Except FREE tracked

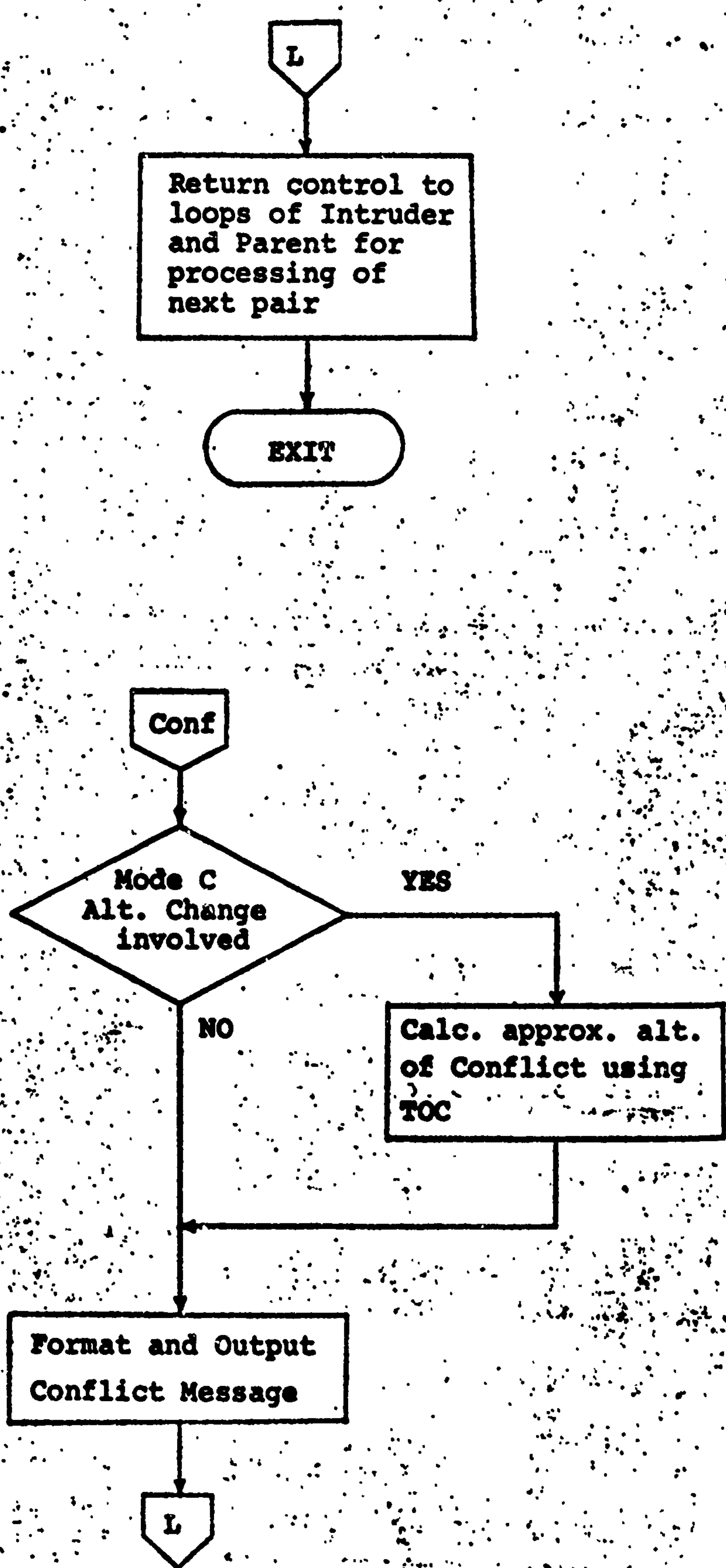

NR
vs
FR
MRSR
FREE Tracked aircraft designated as Intruder
pair pos. coincide
YES
Conf.
NO
Pair safe by GRF
YES
NO
AC converging (RMF)
NO
L
YES
Pair Parallel
YES
PARR FR
NO
Calc. intersection times
angle shallow*
YES
SHALL
NO
5
* Refers to angle of route intersection being < 15°


5
par.
past
intersection
YES
par.
past route
width of int.
YES
NRSP
NO
NO
par.
have turn
before inter-
section
YES
NO
int.
past route
width of par.
YES
NO
sep. at
intersection
meet stand.
YES
NO
NRSP
Conf.

000122


NRS
NRSP
Par. or int. next CTA first
Equal
Parent
Intruder
NRSI
Int. next fix his last fix
YES
YES
Par. next fix his last fix
NO
NO
Int. CTA with-in CSI
NO
NO
Par. CTA with-in CSI
Next fix for either AC their last
YES
L
L
YES
YES
NO
Project Int. pos. and vel. to that of start of next route leg. Push par. equal length of time along current route leg
Project Par. pos. and vel. to that of start of next route leg. Push Int. equal length of time along current route leg
Project each plane's pos. and vel. to start of respective next route leg
NRSR

000123


L
Return control to loops of Intruder and Parent for processing of next pair
EXIT
Conf
Mode C Alt. Change involved
YES
NO
Calc. approx. alt. of Conflict using TOC
Format and Output Conflict Message
L

Appendix D - Altitude Change Rate Determination

A Recursive Estimation of $\dot{Z}$.

We assume that $\dot{Z}$ is constant and that once every seconds (once every radar scan) an observed value h_n of the altitude is furnished by the altimeter. Assume further that $\dot{z}$ has been recursively estimated from n-1 observations $h_1, h_2, \ldots, h_{n-1}$. Denote the estimate of $\dot{z}$ by $\dot{Z}_{n-1}$. Then when h_n is received, $\dot{Z}_n$ can be calculated by the following formulas:

$$F_n = F_n + \omega_n$$

$$G_n = G_{n-1} + F_{n-1}$$

$$H_n = H_{n-1} + 2\,G_{n-1} + F_{n-1}$$

$$J_n = J_{n-1} + \omega_n H_n$$

$$\alpha_n = \frac{\omega_n H_n}{J_n}$$

$$\beta_n = \frac{\omega_n G_n}{J_n}$$

$$\hat{Z}_n = z_{n-1} + \dot{z}_{n-1}$$

$$Z_n = (1-\alpha_n)\,\hat{Z}_n + \alpha_n h_n$$

$$\dot{Z}_n = \dot{Z}_{n-1} + \underline{\beta_n}\,(h_n - \hat{Z}_n)$$

Now $\dot{Z}_n$ is known, as well as all of the quantities necessary to estimate $\dot{Z}_{n+1}$ when h_{n+1} is received.

In these formulas $\omega_n = 1/\sigma_n^2$, where σ_n is the r.m.s. error in the altimeter data. If this is not known we can set $\omega_n = 1$.

If an observation is missed we set $\omega_n = 0$.

To start the process, that is to perform the calculation for n=1 we set

$$F_1 = \omega_1$$

$$G_1 = H_1 = J_1 = 0$$

$$\alpha_1 = 1$$

$$\beta_1 = 0$$

$$Z_1 = h_1$$

$$\dot{Z}_1 = 0$$

The expected r.m.s error in $\dot{Z}$ if the observations h_n are normally distributed with zero mean and the r.m.s error indicated, assuming $= 10$ seconds, is shown in table D-1.

The method for estimating $\dot{Z}$ can be modified to take into account unequal observation intervals as well as the presence of an acceleration component.

Reference: N. Levine "A New Technique for Increasing the Flexability of Recursive Least Squares Data Smoothing" B.S.T.J. (1961) 821-840.

R.M.S. Z Errors/Feet/Sec.

Number of observations	Z errors if r.m.s. altimeter error = 100 ft.
2	14.14
4	4.47
6	2.39
8	1.54
10	1.10
12	.84
14	.615
16	.54
18	.45
20	.39

Table D-1

Appendix E

Conflict Resolution

Excerpt from "Ground Based Collision Avoidance Function For The 1980 Air Traffic Control System"

By Rossman and Kirchoff

2.3 Conflict Resolution

Conflicts will be resolved according to a predetermined hierarchy of aircraft maneuvers. The hierarchy of maneuvers is defined as follows:

- o Lateral Displacement (Vector)
- o Altitude Change
- o Speed Change
- o Holding Pattern

Individual conflicts will not be resolved until approximately 5 minutes before the actual time of the predicted conflict. For two 600 mile/hour aircraft closing head on this translates into a 100 mile separation distance at the time the resolution maneuver is initiated. Conflicts occurring between 5 and 30 minutes will be resolved immediately if one or both of the aircraft involved in the present conflict is also involved in other conflicts. Aircraft which are involved in multiple conflicts will be resolved as soon as they are detected in order to obtain maximum advantage of the 30 minute look ahead time.

If a high number of conflicts are detected, especially if there are a large number of multiple conflicts, a message will be sent to the flow control function. The most probable cause of a

high number of conflicts is an imbalance in the traffic flow. That is, most likely there is too high an aircraft density in one part of the system.

The conflict resolution algorithm must submit each proposed resolution maneuver to the conflict prediction algorithm in order to ensure that the resolution maneuver given is conflict free. Resolution maneuvers will be conflict checked the same way the original conflict is checked. The conflict resolution algorithm for each type of maneuver is described below.

2.3.1 Lateral Displacement

A formula has been derived (see Appendix) which can be used to calculate new heading directions for aircraft in order to avoid conflicts. The formula is given below:

$$\theta' = \frac{(-\tan\theta)(\vec{r}_0\cdot\vec{V}) - (\vec{r}_0\times\vec{V})\cdot\vec{k} + \left[(\vec{r}_0\cdot\vec{V}_A) - (\tan\theta)(\vec{r}_0\times\vec{V}_A)\cdot\vec{k}\right]\theta''}{(-\tan\theta)(\vec{r}_0\times\vec{V}_B)\cdot\vec{k} + (\vec{r}_0\cdot\vec{V}_B)}$$

where:

θ' = angle between the old and new heading of aircraft B

θ'' = angle between the old and new heading of aircraft A

$\vec{V}$ = $\vec{V}_B - \vec{V}_A$ = relative velocity vector between B and A

$\vec{V}_B$ = velocity vector of aircraft B

$\vec{V}_A$ = velocity vector of aircraft A

$\tan\theta = r_m / \sqrt{r_0^2 - r_m^2}$, r_m is the minimum separation distance, r_0 is the initial relative separation.

If $(\vec{r}_o \times \vec{v}) \cdot \vec{k}$ is less than zero, tan θ must be replaced by -tan θ in the above equation. A special case of the above formula is obtaine when only one aircraft's heading is changed. Hence, when $\theta'' = 0$, i.e., when A is unchanged:

$$\theta' = \frac{(\vec{r}_o \times \vec{v}) \cdot \vec{k} + (\tan\theta)(\vec{r}_o \cdot \vec{v})}{-(\vec{r}_o \cdot \vec{v}_B) + (\tan\theta)(\vec{r}_o \times \vec{v}_B) \cdot \vec{k}}$$

and when $\theta' = 0$, i.e., when B is unchanged:

$$\theta'' = \frac{(\vec{r}_o \times \vec{v}) \cdot \vec{k} + (\tan\theta)(\vec{r}_o \cdot \vec{v})}{(\vec{r}_o \cdot \vec{v}_A) - (\tan\theta)(\vec{r}_o \times \vec{v}_A) \cdot \vec{k}}$$

The above formulas are actually small angle approximations, i.e., they are good only when θ' and θ'' are small ($\leq 15°$). In addition, these formulas give the smallest heading change that will resolve the conflict.

A heading change is first tried on only one aircraft. If the conflict cannot be resolved by a small change in either one aircraft or the other, a heading change will be attempted in both aircraft simultaneously. If this fails the next level of maneuvers is tried.

2.3.2 Altitude Change

An altitude change is the second type of maneuver attempted. With this type of maneuver only one aircraft need be moved. There are four possibilities which can be tried - namely, move A up or down, or move B up or down. Aircraft performance characteristics most likely will determine which aircraft should be tried first.

The resolution maneuver is obtained by simply placing the aircraft which is to be moved into the new altitude level and testing for potential conflicts. If no conflicts exist, then the aircraft can be assigned the new altitude level and the conflict is resolved. If, however, there are potential conflicts with all four possibilities it may still be possible 'o resolve the original conflict with an altitude change. For example, in order to resolve the current conflict one of the proposed altitude changes will create a new conflict, say 20 minutes into the future. But the current conflict will occur in 5 minutes. Hence, it may be preferable to resolve the current conflict and "worry" about the new one later since it may never even materialize. If an altitude change is unacceptable then the next level of maneuvers is tried.

2.3.3 Speed Change

A formula has been derived which resolves conflicts by changing the speed of one or both of the aircraft involved in the conflict. Let B represent the ratio of the new speed value to the old speed value for aircraft B. Let A represent the corresponding ratio for aircraft A. Then the ratio $\frac{B}{A}$ is a constant and is given by the formula below:

$$\frac{B}{A} = \frac{(\vec{r}_0 \times \vec{V}_A)\cdot\vec{k} + (\tan\theta)(\vec{r}_0\cdot\vec{V}_A)}{(\vec{r}_0 \times \vec{V}_B)\cdot\vec{k} \pm (\tan\theta)(\vec{r}_0\cdot\vec{V}_B)}$$

Hence, if A = 1 (meaning A's speed is unchanged) we have a formula for the speed change which must be imposed upon B

in order to resolve the conflict. Likewise setting B = 1 we obtain the corresponding value of A which is needed to resolve the conflict. The above formula can be used separately on each of the aircraft. If neither change is compatible with the aircraft's characteristics, an attempt will be made to change both aircraft simultaneously. If this is not feasible the next level of maneuvers is tried.

2.3.4 Holding Pattern

If all maneuvers above have failed, then a holding pattern will be imposed upon one of the aircraft. This maneuver will result in a time delay for the aircraft being held. This maneuver should not be used very often since most conflicts can be resolved in the enroute airspace by the first two types of maneuvers.

2.3.5 Computer Timing and Storage Estimates

A flow diagram of the conflict resolution algorithm is shown in Figure 2-3. The computer timing estimates given below were made for an assumed "worst" case and for an assumed "average" case. Actually almost 100% of the conflict resolution time is consumed by testing the proposed resolution maneuver to see if it is conflict free. Hence the conflict prediction timing estimates given in Section 2.2.6.2 were used to determine the conflict resolution times.

Figure 2-3(a)

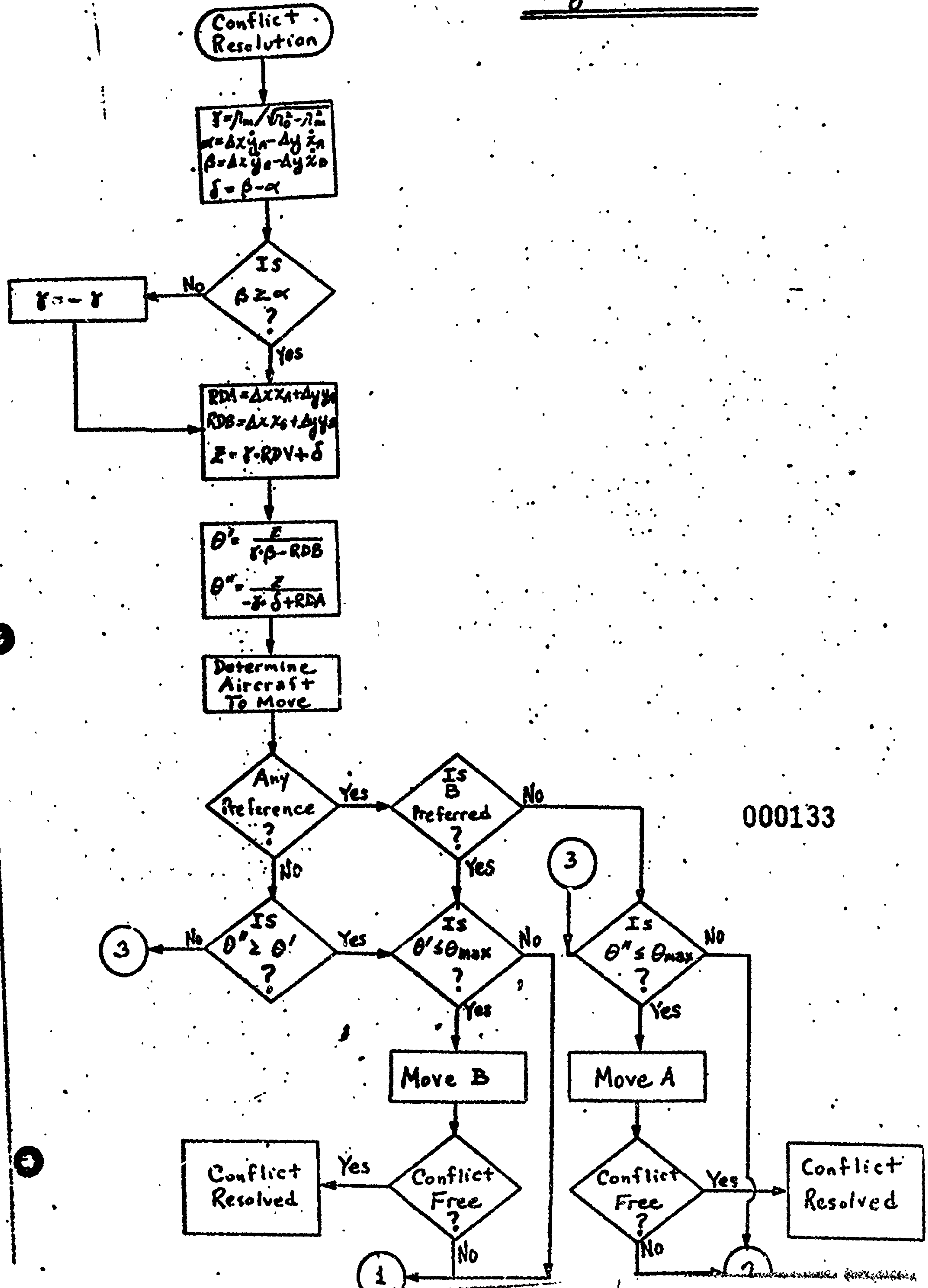


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Figure 2-3 (c)

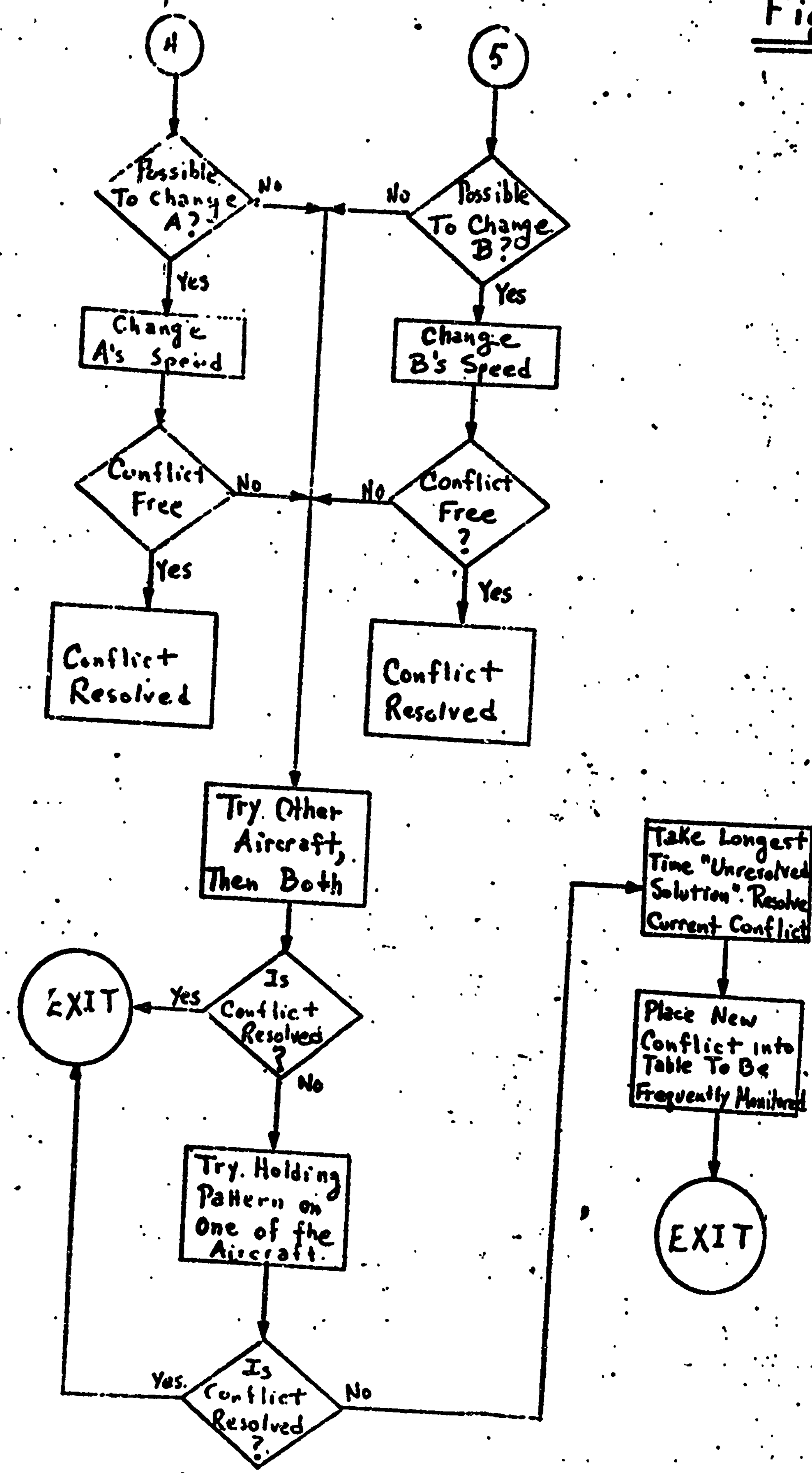

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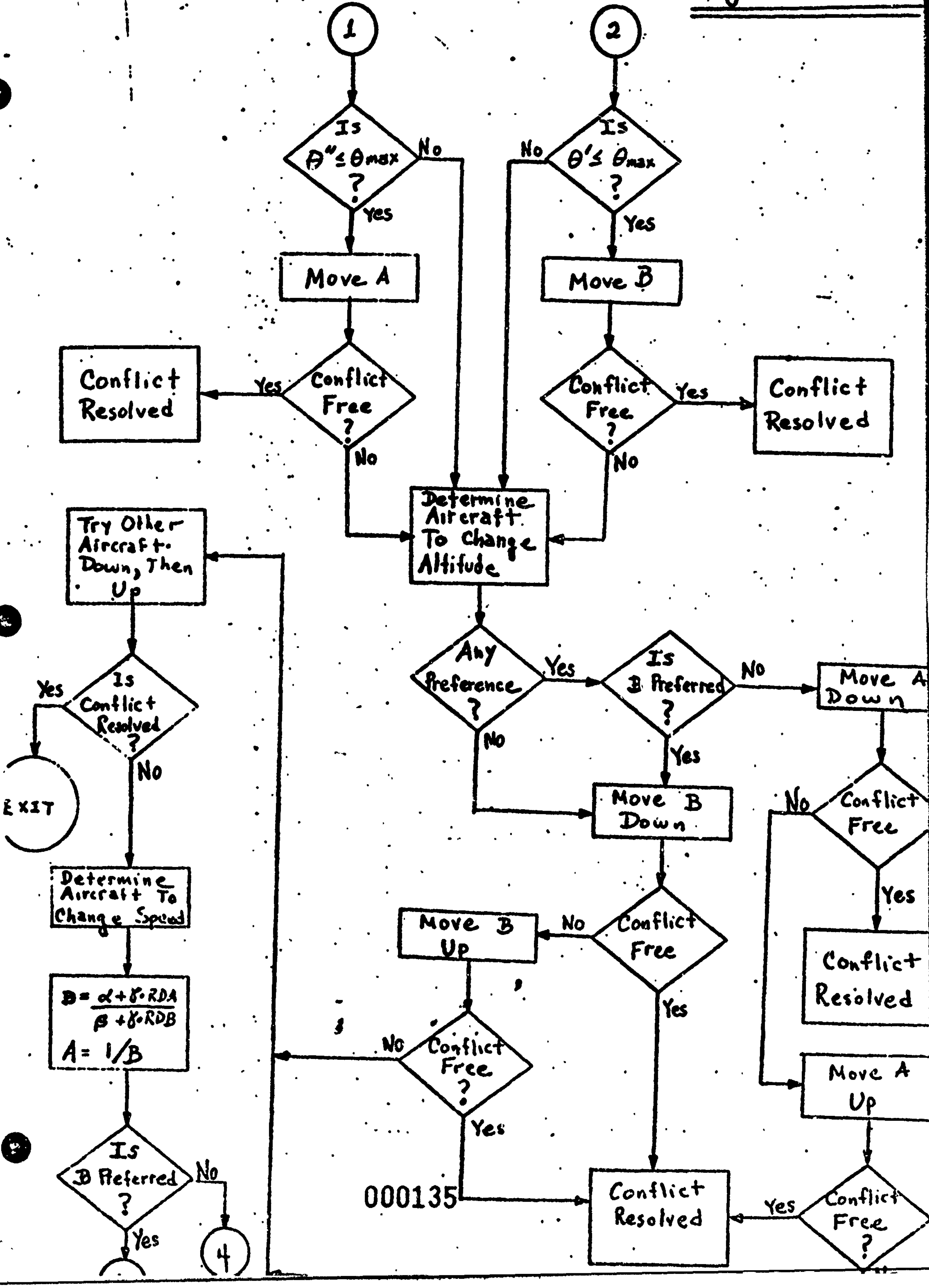
Figure 2-3 (b)



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CONFLICT RESOLUTION

Lateral Displacement

In Figure 2-1, if the straight line equation, represented by the relative velocity vector, $\vec{V}$, cuts the circle of protection about A, then a conflict will occur at some future point in time. In order to resolve this conflict the direction of the relative velocity vector must be changed in such a manner as to fall outside the circle of protection. The minimum change possible would be to have the extrapolation of the relative velocity vector just tangent to the circle of protection. This can be accomplished by changing the heading of aircraft A or B, or both. An equation is derived below which enables the minimum heading change of both A and B to be calculated. The following symbols are used below in the derivation of the equation:

$\vec{V}_B$ = old velocity vector of B

$\vec{V}^1_B$ = new velocity vector of B

$\vec{V}_A$ = old velocity vector of A

$\vec{V}^1_A$ = new velocity vector of A

$\vec{V} = \vec{V}_B - \vec{V}_A$ = old relative velocity vector

$\vec{V}^1 = \vec{V}^1_B - \vec{V}^1_A$ = new relative velocity vector (tangent to the circle of protection).

$\vec{k}$ = unit vector in the z direction

θ = angle between $\vec{r}_o$ and $\vec{V}^1$,

θ' = angle between $\vec{V}_B$ and $\vec{V}^1_B$

θ'' = angle between $\vec{V}_A$ and $\vec{V}^1_A$

Θ_{RB} = angle between $\vec{r}_o$ and $\vec{V}_B$

Θ_{RA} = angle between $\vec{r}_o$ and $\vec{V}_A$

Figure A-1 illustrates the symbols defined above. Since only the heading (direction) of A and B are changed, $|\vec{V}_B'| = |\vec{V}_B|$, and $|\vec{V}_A'| = |\vec{V}_A|$.

From Figure A-1

$$
\begin{aligned}
(\vec{r}_o \times \vec{V}')\cdot\vec{k} &= |\vec{r}_o||\vec{V}'|\sin(\pi-\theta) \\
&= |\vec{r}_o||\vec{V}'|\sin\theta, \text{ if } (\vec{r}_o\times\vec{V})\cdot\vec{k} \geq 0 \\
&= |\vec{r}_o||\vec{V}'|\sin(\pi+\theta) \\
&= -|\vec{r}_o||\vec{V}'|\sin\theta, \text{ if } (\vec{r}_o\times\vec{V})\cdot\vec{k} < 0
\end{aligned} \tag{1}
$$

Also

$$
\begin{aligned}
(\vec{r}_o\cdot\vec{V}') &= |\vec{r}_o||\vec{V}'|\cos(\pi-\theta) \\
&= -|\vec{r}_o||\vec{V}'|\cos\theta, \text{ if } (\vec{r}_o\times\vec{V})\cdot\vec{k} \geq 0 \\
&= |\vec{r}_o||\vec{V}'|\cos(\pi+\theta) \\
&= -|\vec{r}_o||\vec{V}'|\cos\theta, \text{ if } (\vec{r}_o\times\vec{V})\cdot\vec{k} < 0
\end{aligned} \tag{2}
$$

The ratio of (1) to (2) yields,

$$\frac{(\vec{r}_o\times\vec{V}')\cdot\vec{k}}{\vec{r}_o\cdot\vec{V}'} = -\tan\theta, \text{ if } (\vec{r}_o\times\vec{V})\cdot\vec{k} \geq 0 \tag{3a}$$

$$+\tan\theta, \text{ if } (\vec{r}_o\times\vec{V})\cdot\vec{k} < 0 \tag{3b}$$

Since, $\vec{V}' = \vec{V}_B' - V_A'$, we have

$$\frac{(\vec{r}_o \times \vec{V}_B')\cdot\vec{k} - (\vec{r}_o \times \vec{V}_A')\cdot\vec{k}}{(\vec{r}_o\cdot\vec{V}_B') - (\vec{r}_o\cdot\vec{V}_A')} = -\tan\theta$$

But,

$$\begin{aligned}(\vec{r}_o \times \vec{V}_B')\cdot\vec{k} &= |\vec{r}_o||\vec{V}_B'|\sin(\theta_{RB}+\theta') \\ &= |\vec{r}_o||\vec{V}_B|\left[\sin\theta_{RB}\cos\theta' + \cos\theta_{RB}\sin\theta'\right] \\ &= |\vec{r}_o||\vec{V}_B|\left[\frac{(\vec{r}_o\times\vec{V}_B)\cdot\vec{k}\cos\theta'}{|\vec{r}_o||\vec{V}_B|} + \frac{(\vec{r}_o\cdot\vec{V}_B)\sin\theta'}{|\vec{r}_o||\vec{V}_B|}\right] \\ &= (\vec{r}_o\times\vec{V}_B)\cdot\vec{k}\cos\theta' + (\vec{r}_o\cdot\vec{V}_B)\sin\theta' \end{aligned} \tag{4}$$

Likewise for $(\vec{r}_o \times \vec{V}_A')\cdot\vec{k}$ we obtain

$$(\vec{r}_o \times \vec{V}_A')\cdot\vec{k} = (\vec{r}_o\times\vec{V}_A)\cdot\vec{k}\cos\theta'' + (\vec{r}_o\cdot\vec{V}_A)\sin\theta'' \tag{5}$$

Now,

$$\begin{aligned}\vec{r}_o\cdot\vec{V}_B' &= |\vec{r}_o||\vec{V}_B'|\cos(\theta_{RB}+\theta') \\ &= |\vec{r}_o||\vec{V}_B|\left[\cos\theta_{RB}\cos\theta' - \sin\theta_{RB}\sin\theta'\right] \\ &= |\vec{r}_o||\vec{V}_B|\left[\frac{(\vec{r}_o\times\vec{V}_B)\cdot\vec{k}\cos\theta'}{|\vec{r}_o||\vec{V}_B|} - \frac{(\vec{r}_o\cdot\vec{V}_B)\sin\theta'}{|\vec{r}_o||\vec{V}_B|}\right] \\ &= (\vec{r}_o\cdot\vec{V}_B)\cos\theta' - (\vec{r}_o\times\vec{V}_B)\cdot\vec{k}\sin\theta' \end{aligned} \tag{6}$$

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Similarly,

$$(\vec{r}_0 \cdot \vec{V}_A') = (\vec{r}_0 \cdot \vec{V}_A)\cos\theta'' - (\vec{r}_0 \times \vec{V}_A)\sin\theta'' \tag{7}$$

Substituting (4), (5), (6), and (7) into (3a) we obtain:

$$\frac{(\vec{r}_0 \times \vec{V}_B)\cdot\vec{k}\cos\theta' + (\vec{r}_0 \cdot \vec{V}_B)\sin\theta' - (\vec{r}_0 \times \vec{V}_A)\cdot\vec{k}\cos\theta'' - (\vec{r}_0 \cdot \vec{V}_A)\sin\theta''}{(\vec{r}_0 \cdot \vec{V}_B)\cos\theta' - (\vec{r}_0 \times \vec{V}_B)\cdot\vec{k}\sin\theta' - (\vec{r}_0 \cdot \vec{V}_A)\cos\theta'' + (\vec{r}_0 \times \vec{V}_A)\cdot\vec{k}\sin\theta''} = -\tan\theta$$

If θ' and θ'' are both small then,

$$\sin\theta' \cong \theta' \quad , \quad \cos\theta' \cong 1$$
$$\sin\theta'' \cong \theta'' \quad , \quad \cos\theta'' \cong 1$$

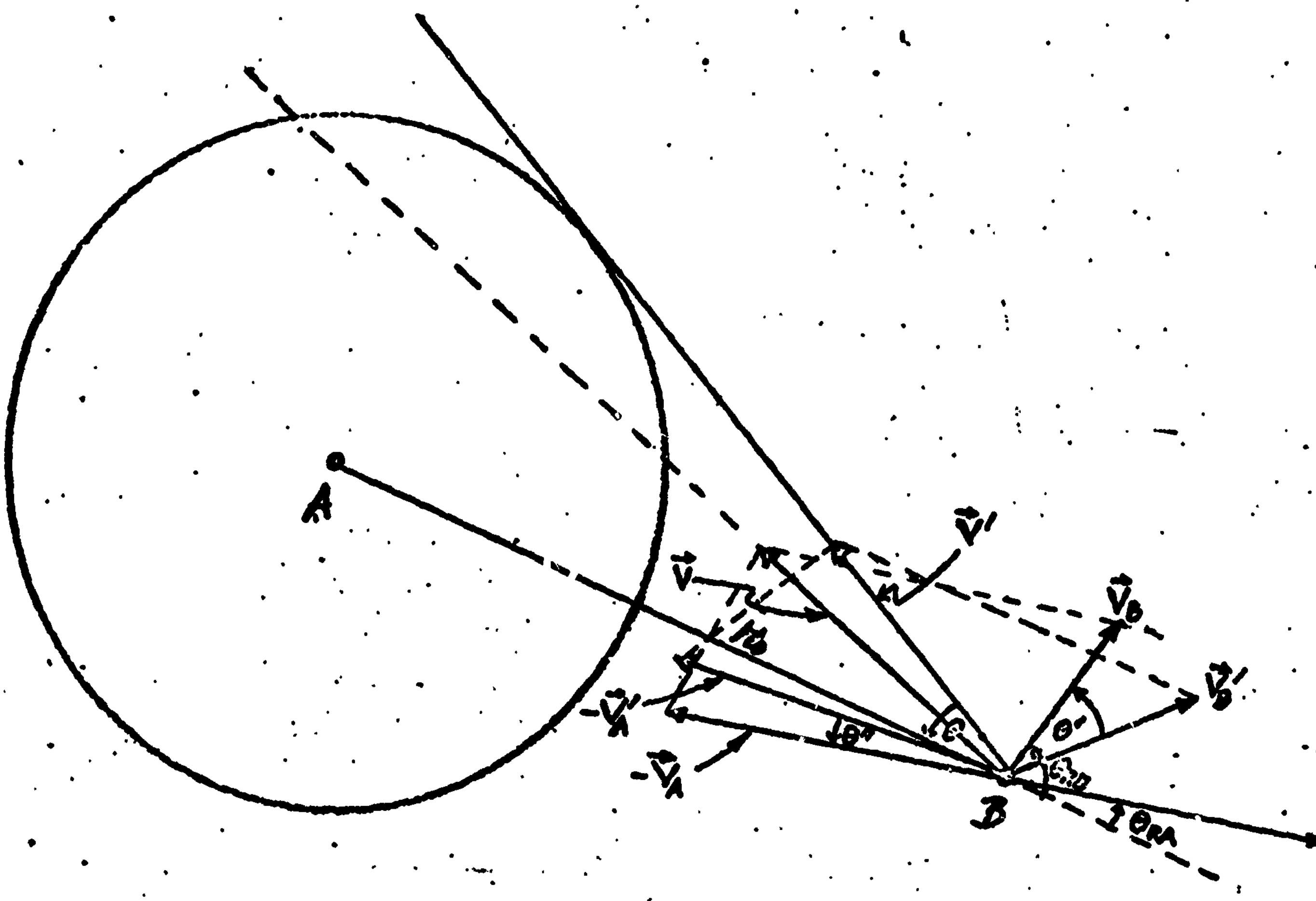
and the above reduces to:

$$\frac{(\vec{r}_0 \times \vec{V})\cdot\vec{k} + (\vec{r}_0 \cdot \vec{V}_B)\theta' - (\vec{r}_0 \cdot \vec{V}_A)\theta''}{(\vec{r}_0 \cdot \vec{V}) - (\vec{r}_0 \times \vec{V}_B)\cdot\vec{k}\,\theta' + (\vec{r}_0 \times \vec{V}_A)\cdot\vec{k}\,\theta''} = -\tan\theta \tag{8}$$

Finally,

$$\boxed{\theta' = \frac{(-\tan\theta)(\vec{r}_0 \cdot \vec{V}) - ((\vec{r}_0 \times \vec{V})\cdot\vec{k}) + \left[(-\tan\theta)(\vec{r}_0 \times \vec{V}_A)\cdot\vec{k} + (\vec{r}_0 \cdot \vec{V}_A)\right]\theta''}{(-\tan\theta)((\vec{r}_0 \times \vec{V}_B)\cdot\vec{k}) + (\vec{r}_0 \cdot \vec{V}_B)}} \tag{9}$$

where $\tan\theta = r_m / \sqrt{r_0^2 - r_m^2}$ (The sign of $\tan\theta$ being determined by the sign of $(\vec{r}_0 \times \vec{V})\cdot\vec{k}$. If θ' or θ'' is set equal to zero the above formula reduces to the case where only one aircraft's heading is changed. Since equation (9) involves two variables one must be predetermined before solving for the second.



HEADING CHANGE

Figure A-1

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Speed Changes

Changing the magnitude only of the velocity vectors $\vec{V}_A$ and $\vec{V}_B$ changes both the magnitude and direction of the vector $\vec{V}$. We seek constants A and B such that the direction of the new relative velocity vector, $\vec{V}' = B\vec{V}_B - A\vec{V}_A$, is tangent to the circle of protection about A (see Figure A-2).

Hence:

$$B = \frac{|\vec{V}_B'|}{|\vec{V}_B|}, \quad A = \frac{|\vec{V}_A'|}{|\vec{V}_A|}$$

Following our earlier derivation we have:

$$\frac{(\vec{r}_o \times \vec{V}')\cdot \vec{k}}{(\vec{r}_o \cdot \vec{V}')} = -\tan\theta, \text{ if } (\vec{r}_o \times \vec{V})\cdot \vec{k} \geq 0 \qquad \text{(10a)}$$

$$+\tan\theta, \text{ if } (\vec{r}_o \times \vec{V})\cdot \vec{k} < 0 \qquad \text{(10b)}$$

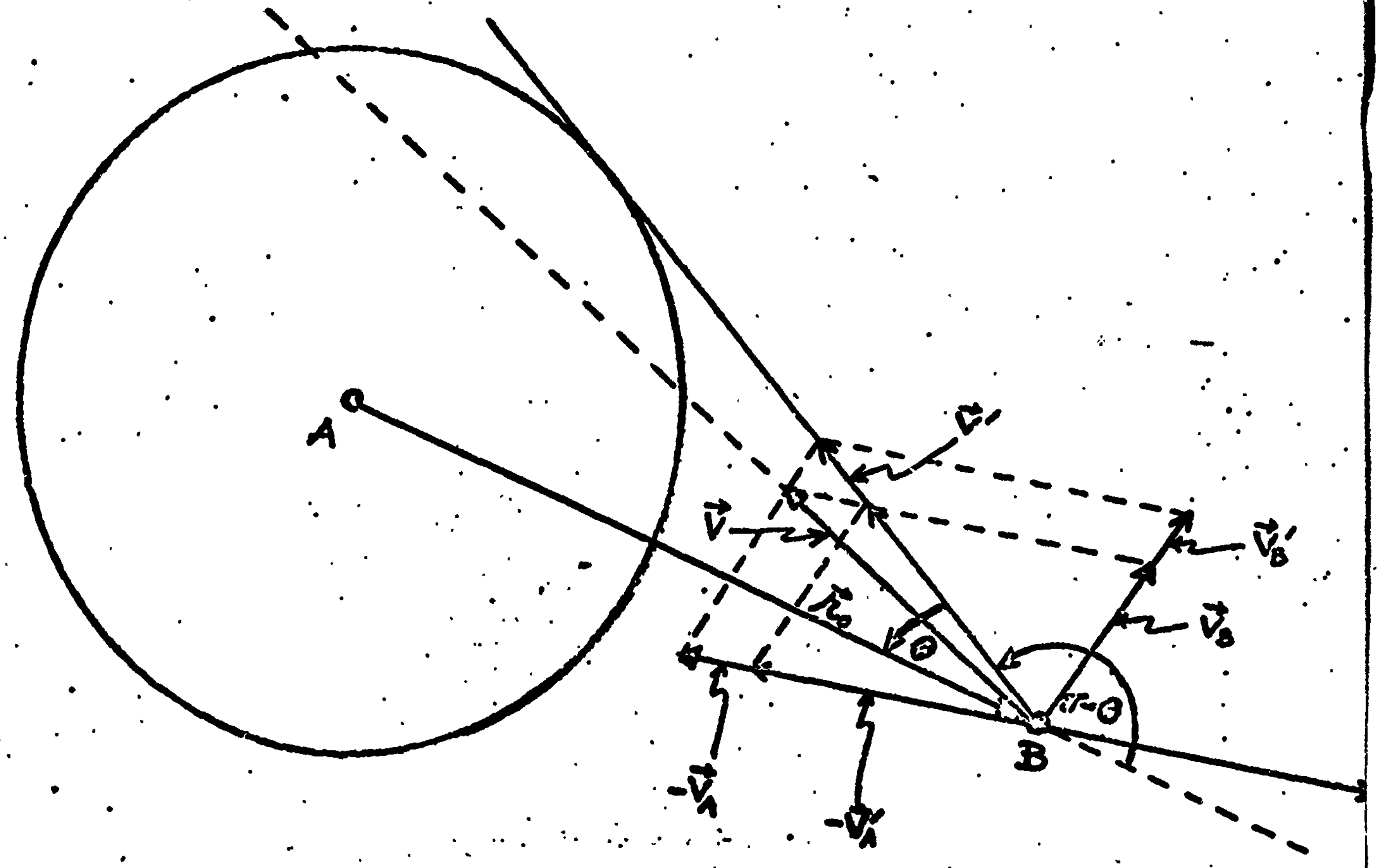
Substituting $\vec{V}' = B\vec{V}_B - A\vec{V}_A$ into (10a) we have:

$$\frac{\vec{r}_o \times (B\vec{V}_B - A\vec{V}_A)\cdot \vec{k}}{\vec{r}_o \cdot (B\vec{V}_B - A\vec{V}_A)} = -\tan\theta$$

$$\frac{B(\vec{r}_o \times \vec{V}_B)\cdot \vec{k} - A(\vec{r}_o \times \vec{V}_A)\cdot \vec{k}}{B(\vec{r}_o \cdot \vec{V}_B) - A(\vec{r}_o \cdot \vec{V}_A)} = -\tan\theta$$

Cross multiplying the above we obtain:

$$B(\vec{r}_o \times \vec{V}_B)\cdot \vec{k} - A(\vec{r}_o \times \vec{V}_A)\cdot \vec{k} = -\tan\theta\left[B(\vec{r}_o \cdot \vec{V}_B) - A(\vec{r}_o \cdot \vec{V}_A)\right]$$



<u>**SPEED CHANGE**</u>

Figure A-2

and finally,

$$\boxed{\frac{B}{A} = \frac{(\vec{r}_0 \times \vec{v}_A)\cdot\vec{k} + \tan\theta\,(\vec{r}_0\cdot\vec{v}_A)}{(\vec{r}_0 \times \vec{v}_B)\cdot\vec{k} + \tan\theta\,(\vec{r}_0\cdot\vec{v}_B)}} \tag{11}$$

Setting A=1, (i.e., A's speed is unchanged) we can solve for the value of B. Note the ratio B/A is a constant since everything on the right hand side of (11) is a constant.